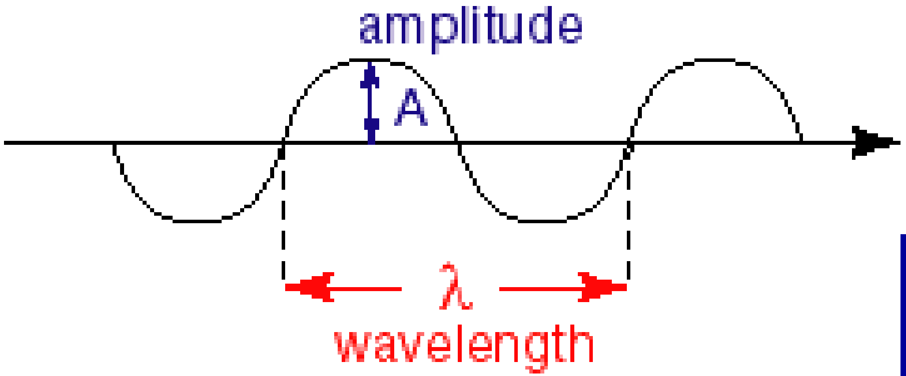
High Power Ultrasonics

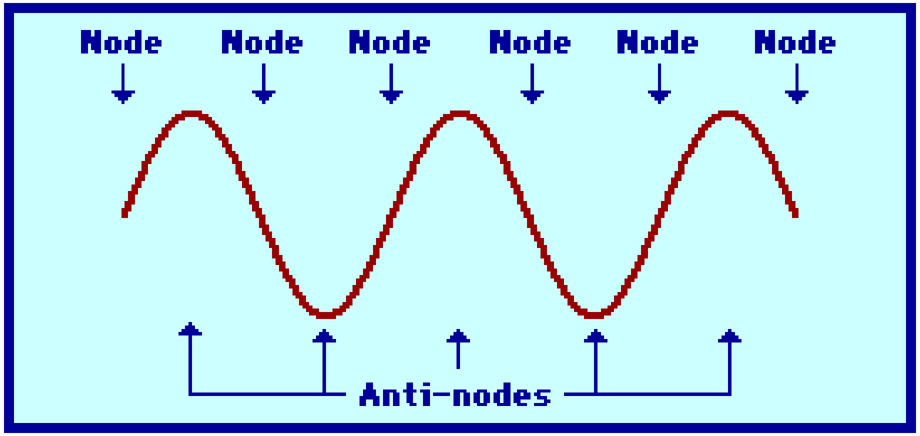
David Grewell
Iowa State University

Overview

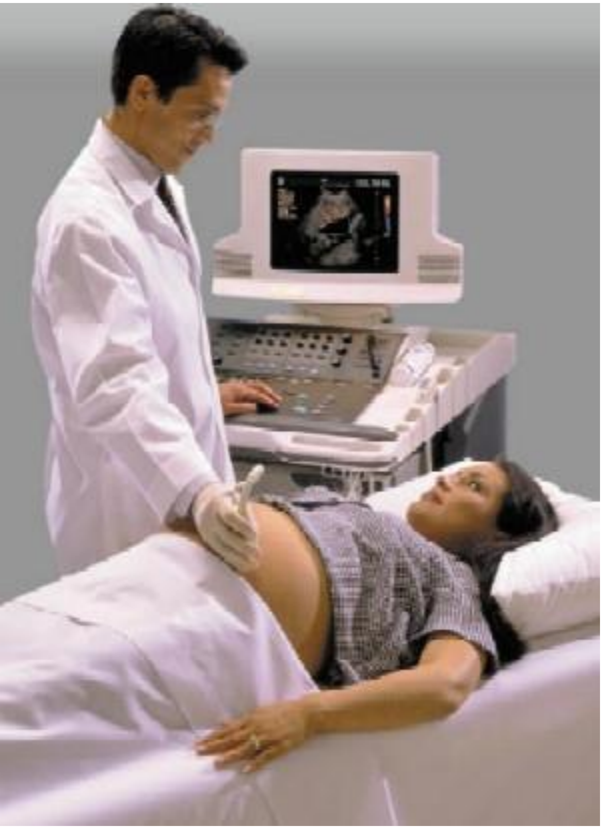
- Ultrasonics
- Generation
- Effects
- Applications

- > 20 kHz


amplitude
A
λ
wavelength


Node
Node
Node
Node
Node
Node
Anti-nodes

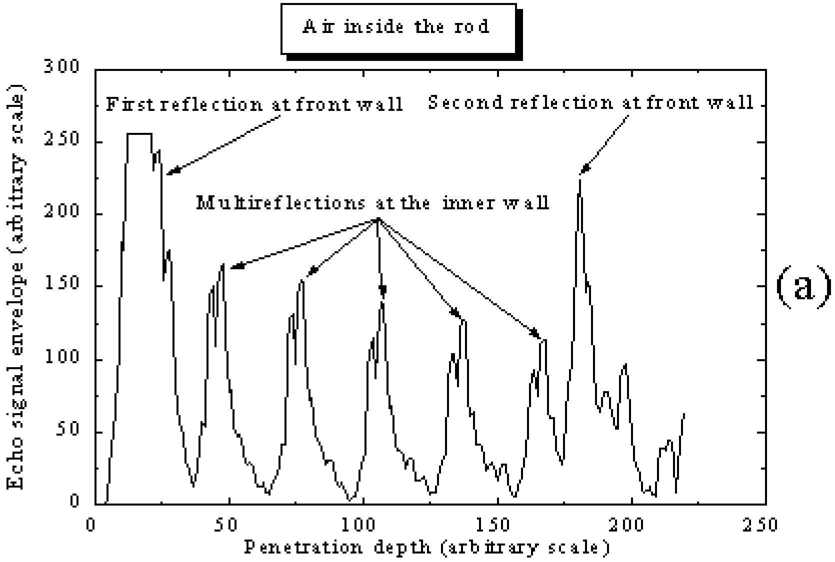
- Most familiar application(1.6 to 10 MHz-GHz)

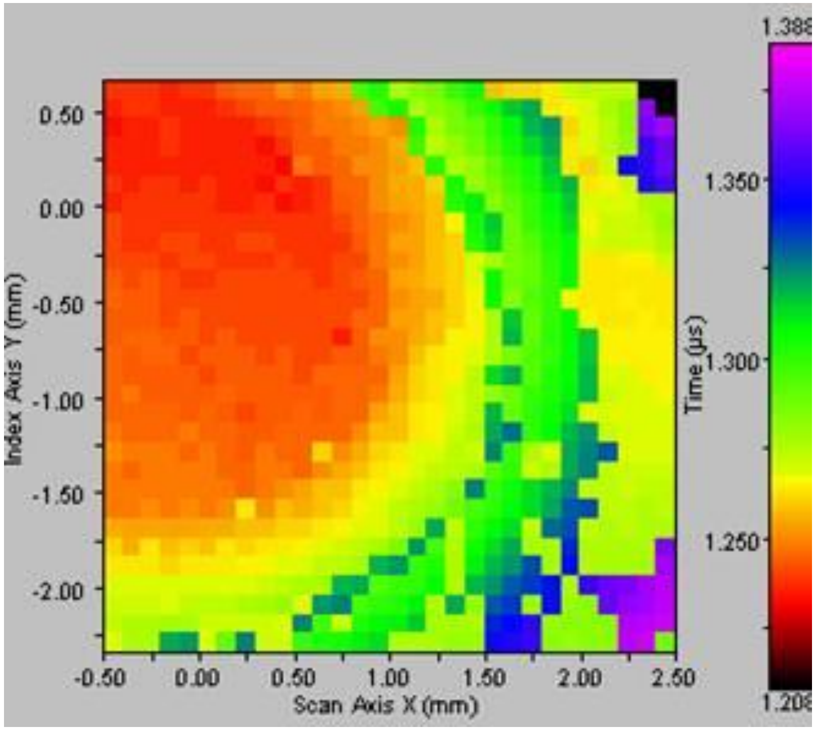


Images from Wikipedia

C-scan

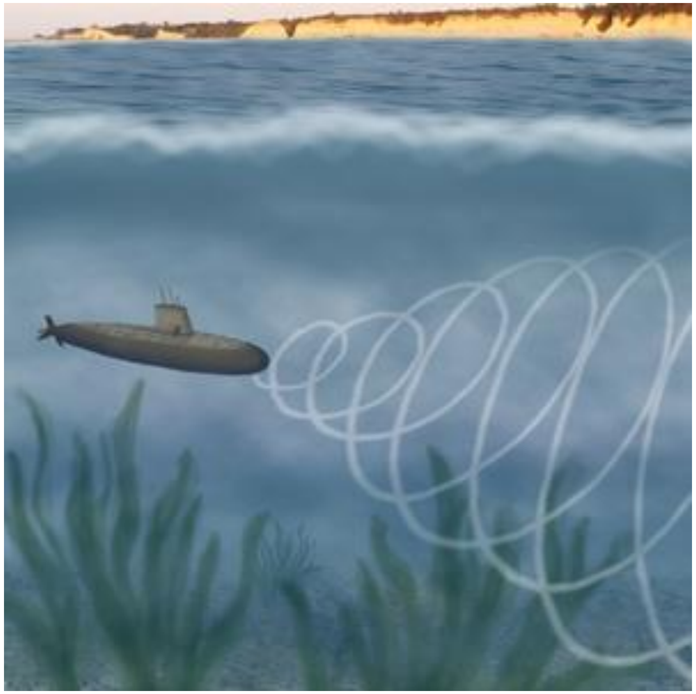
Listen for echoes and scan in 2-D
Total of 3-D image





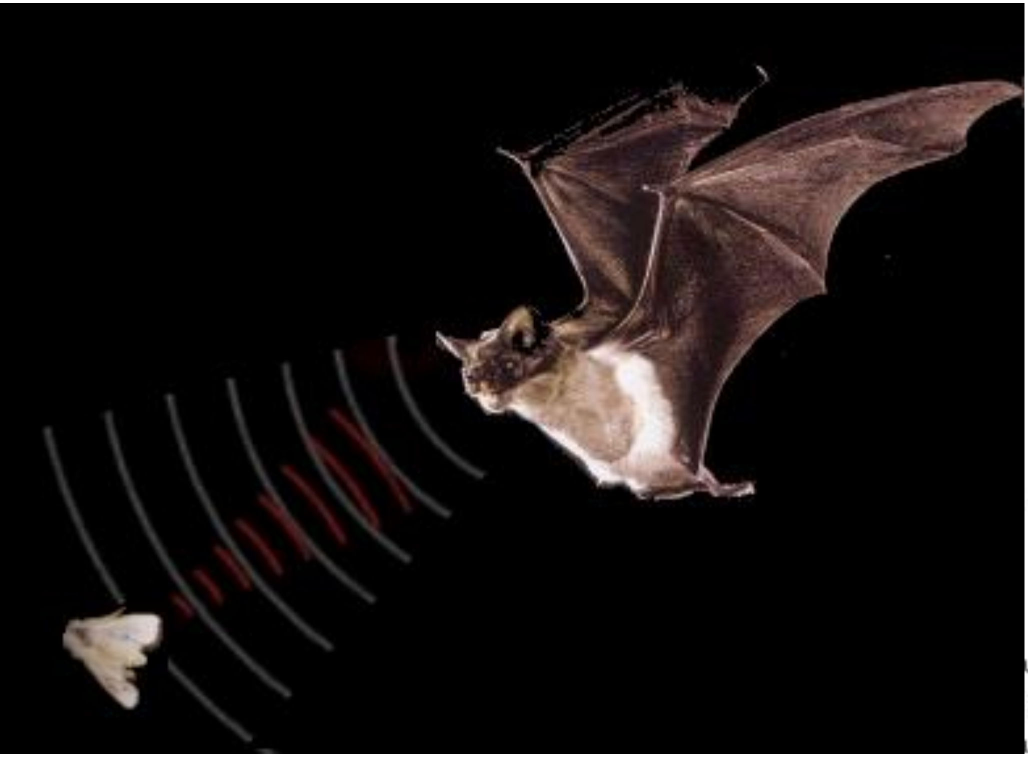
Images from Wikipedia

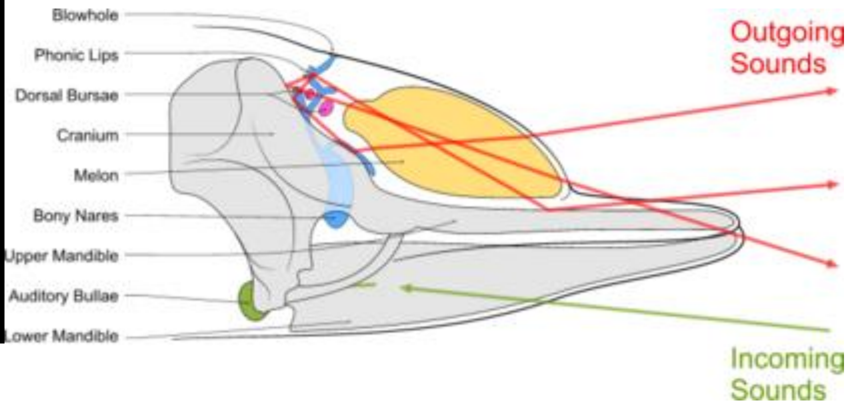
- Most familiar application(50 to 100 kHz)



Images from Wikipedia

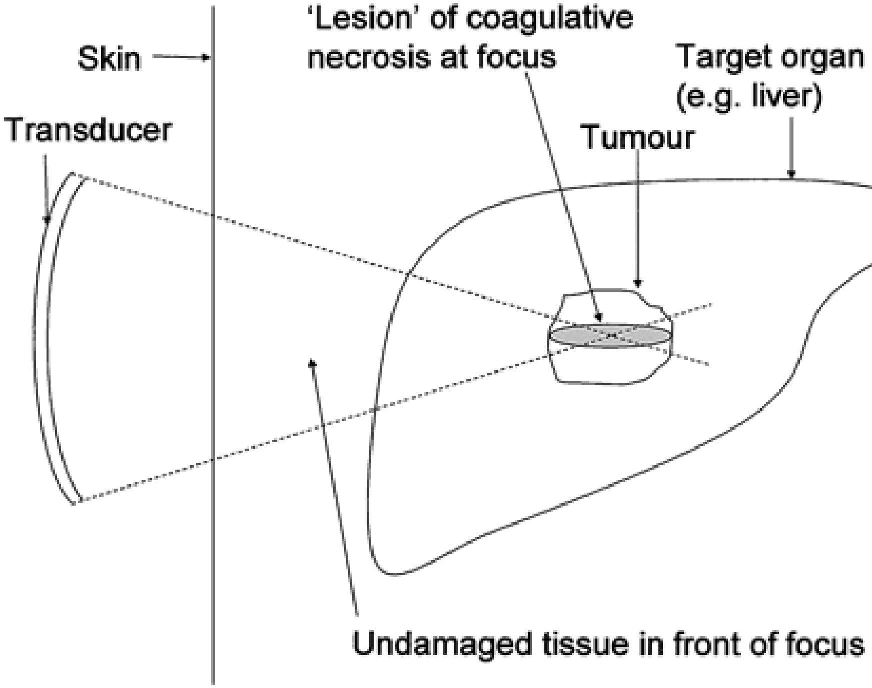
- Most familiar application (bats 14 to 150 kHz)



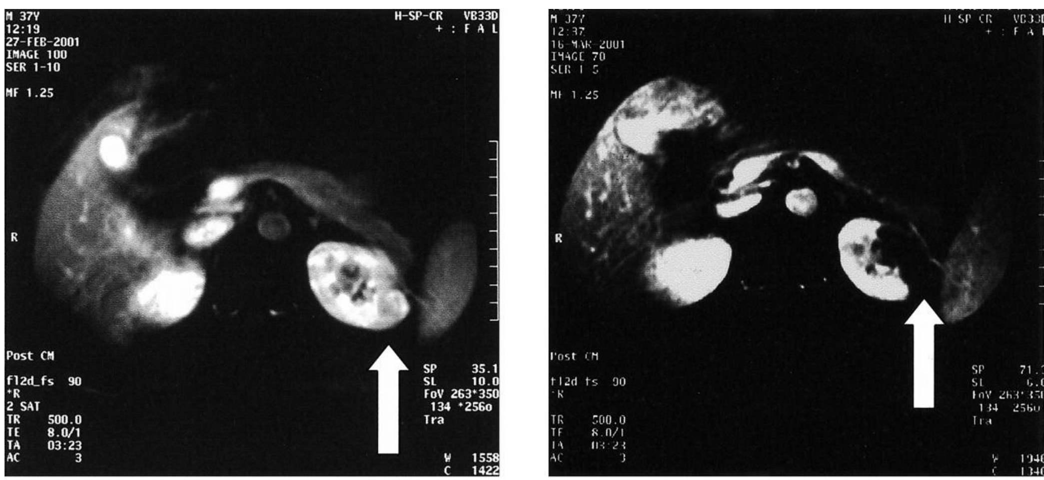


Images from Wikipedia

- Stone, tissue destruction (1 to 20 W)



Treatment of retina tumor

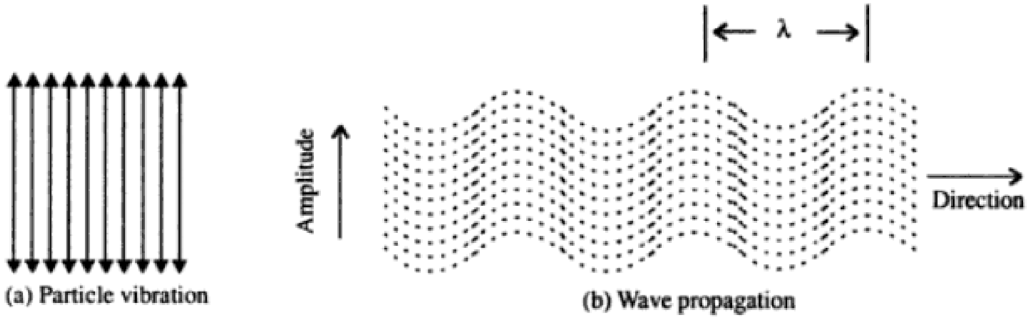


(a) (b)

Images from Wikipedia

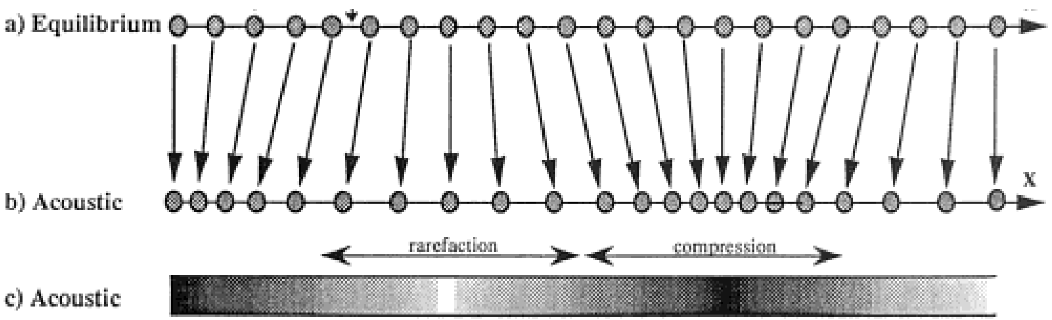
Waves

Longitudinal waves



Baldev. R., Palanichamy. P., Rajendran. V., Pg 10 “Science and technology of ultrasonics” (2003)

Compressional waves



$$c = \sqrt{\left(\frac{E}{\rho}\right)}$$

Speed of sound in air and water are 343m/s and 1484 m/s

Baldev. R., Palanichamy. P., Rajendran. V., Pg 10 "Science and technology of ultrasonics" (2003)

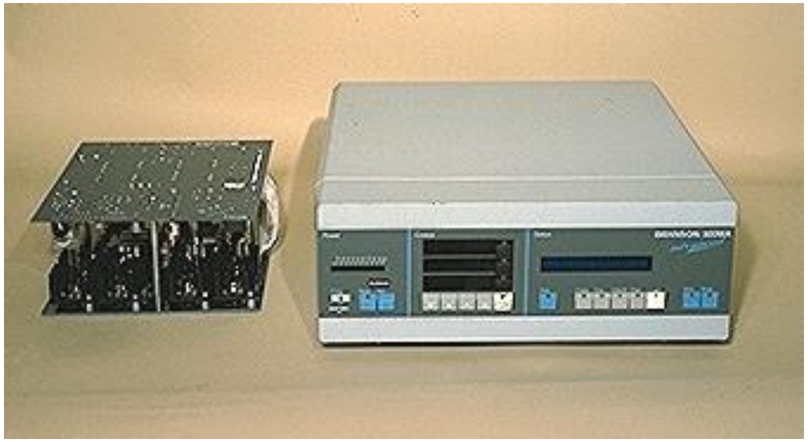
Equipment

Ultrasonic equipment

- **Power Supply**
- **Control Level**
- **Actuator/Stand**
- **Converter**
- **Booster**
- **Horn**
- **Fixture**

Ultrasonic power supply

- Controller (Modular design)
  - Human interface
  - I/O, PLC
  - SPC/Data ACQ.
- Power module
  - Line conversion
  - Tuning
  - O/L Protection



Graphics: Branson Ultrasonics

Branson Ultrasonics

Standard system

- Modular design
- Remote power supply
- Remote controls
- Easy for system integration

Graphics: Branson Ultrasonics

Branson Ultrasonics

Ultrasonic power supplies

- All suppliers offer various control levels:
  - Basic for PLC control
  - Time
  - Distance, Time, Power, Etc
- Application dependent

Graphics: Branson Ultrasonics

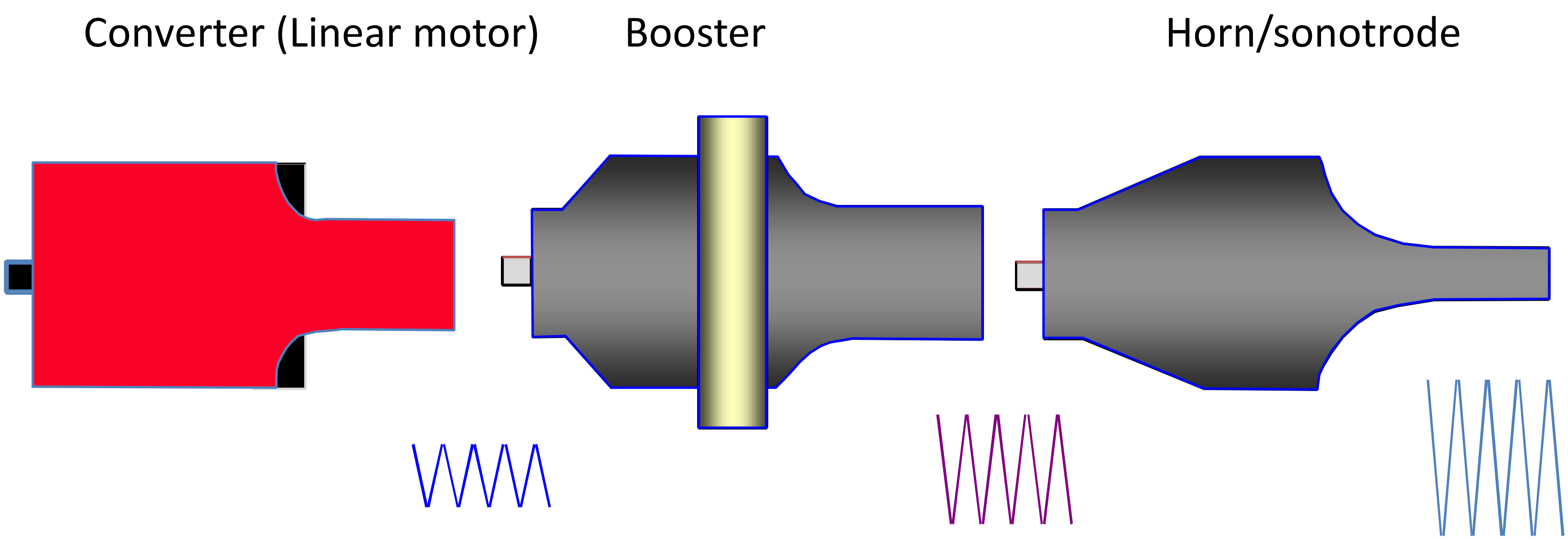
Actuator

- Applies welding force
- Pressure regulator
  - Maximum force
- Flow control
  - Down speed
  - Force buildup
- Stack mounting
- Encoder

Graphics: Branson Ultrasonics

Stack

- Three major components:



Graphics: Branson Ultrasonics

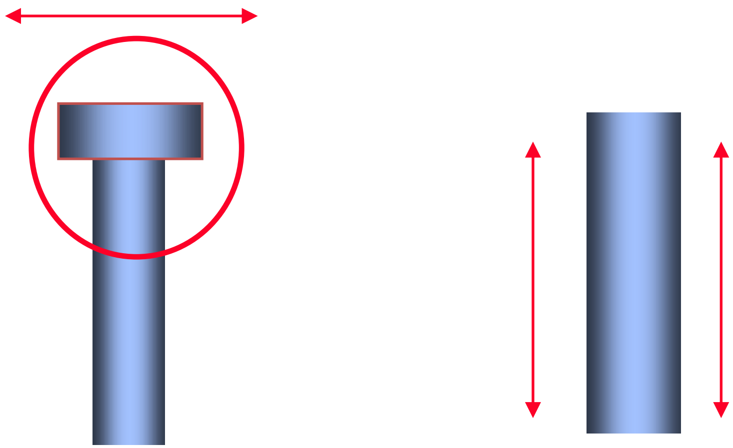
Branson Ultrasonics

Stack and resonance

- All parts are tuned to one frequency
- The system operators at resonance

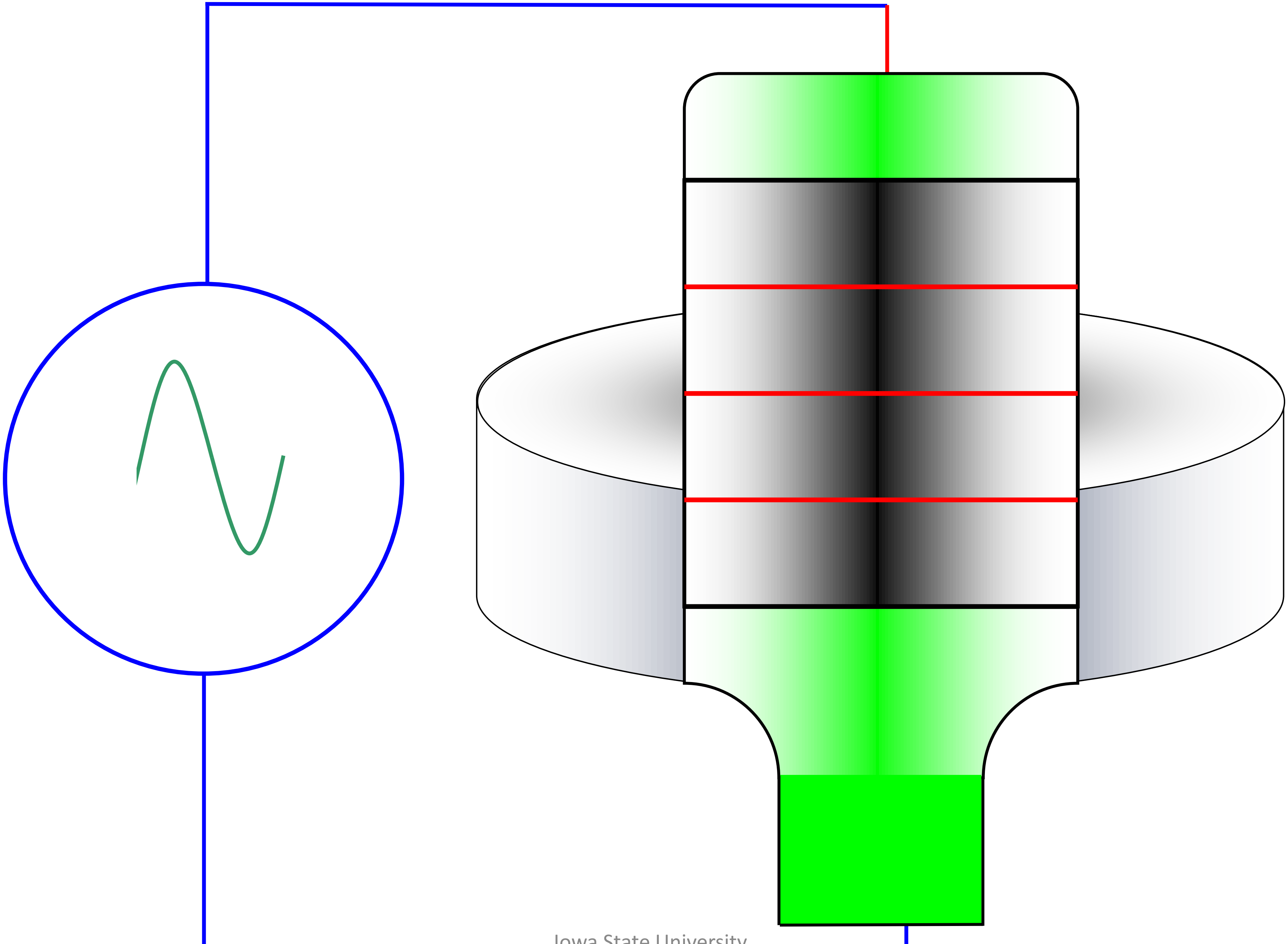
Stack vibrations

- Axial is the ideal mode for ultrasonic welding
- All component are design as resonators
- All other modes tend to:
  - Reduce efficiency
  - Promote failure



Graphics: Branson Ultrasonics

Converters



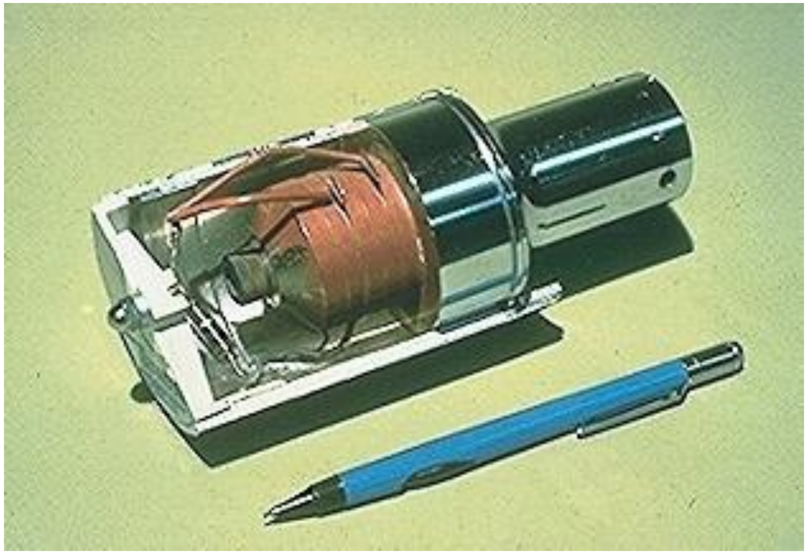
Converter/Transducer

- Heart of the system
- Converters electrical energy to mechanical
- Motor
- 90 to 97% efficient
- Most are piezo-electric

Graphics: Branson Ultrasonics

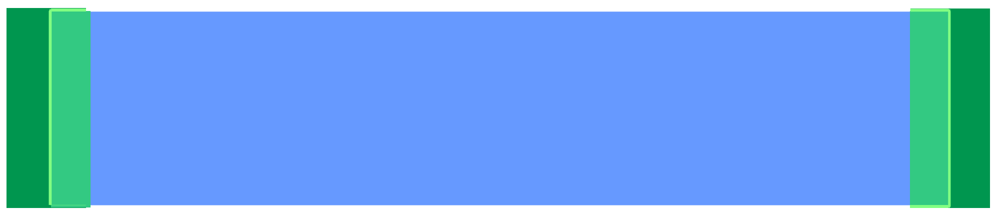
Converter

- Most are piezo-electric
  - High voltage (1-5 KV)
  - Ceramic crystals
  - (½ λ)
- Less popular are magnetostrictive

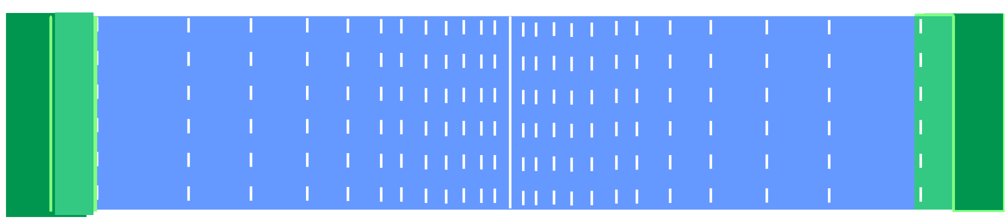


Graphics: Branson Ultrasonics

Stack output



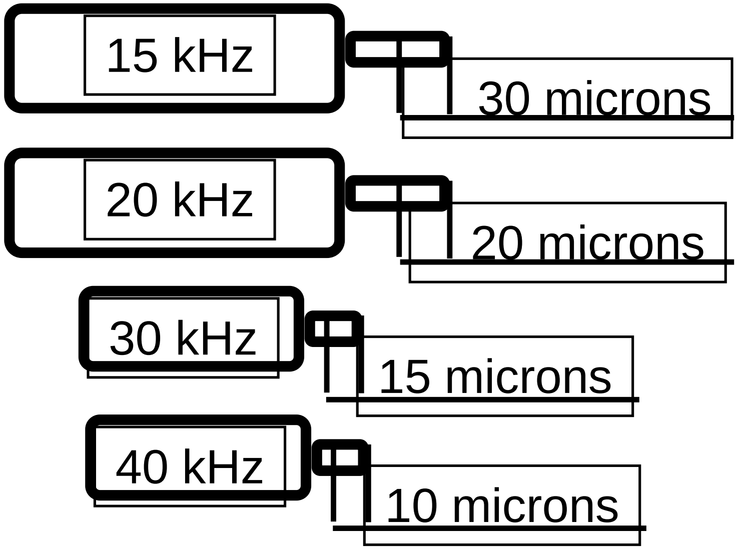
Amplitude (P-P)



Graphics: Branson Ultrasonics

Typical converter output

- Peek to Peek amplitude
- At 100% output:



Converter characteristics

- Maximum power
- Frequency
- Efficiency
- Cooling
  - Forced air
  - Static Air

Converter failures

- Off modes of vibration/wrong frequency
  - Usually in the horn
- Impact
  - Jack hammering
  - Contact with fixture
- Cooling
  - No air
  - Poor design

Boosters & Horns

Boosters

- Mechanical amplifier
- Discreet factors
- Materials:
  - Al: Cost effective
  - Ti: Tough applications
- Mounting point of stack

Graphics: Branson Ultrasonics

Booster/horn gain

- Ratio of volume above and below nodal plane

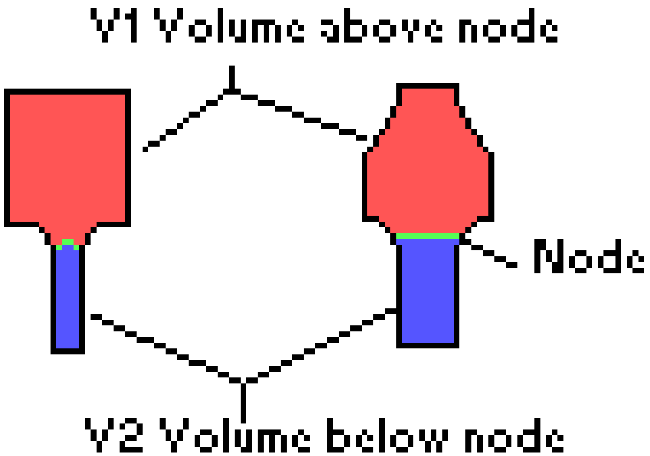
$$F = ma$$

From equilibrium:

$$F_1 = F_2 \Rightarrow m_1 a_1 = m_2 a_2$$

$$\frac{m_1}{m_2} = \frac{a_2}{a_1} = Gain$$

Measure volume using liquid displacement method



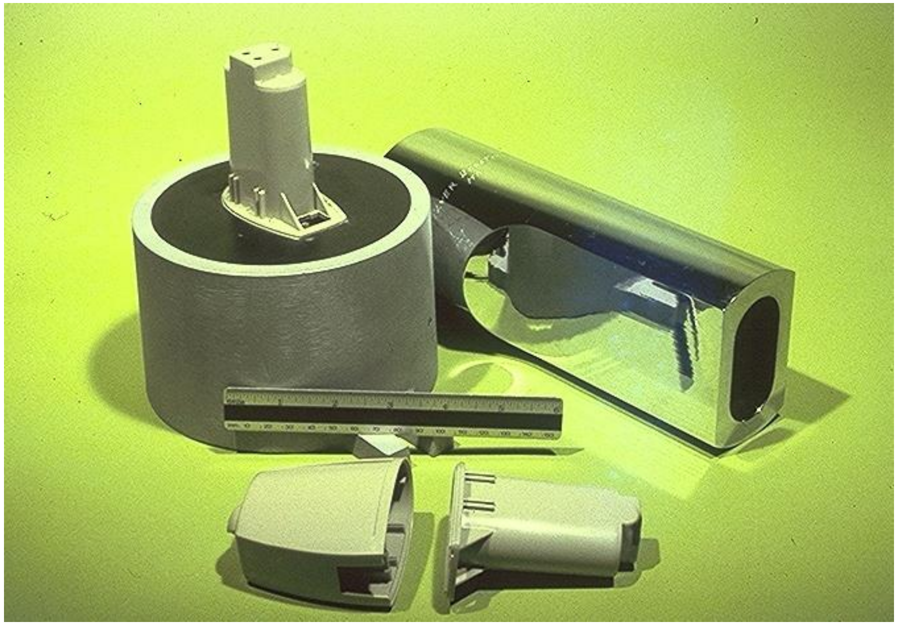
Horns/Sonotrodes

- Applies:
  - Ultrasonic energy
  - Force
- Tuned (½ and full λ)
- Material
  - Al:Cost effective
  - Ti: High gain
  - Steel: High wear
  - Ferro-Tec
  - Coated: High wear

Graphics: Branson Ultrasonics

Horns (Half and full λ)

- Application dependent
- Allows welding internal to the application



Graphics: Branson Ultrasonics

Horns (Full λ)

- Application dependent
- Allows welding internal to the application

Graphics: Branson Ultrasonics

Horns-replacement tips

- Cost effective solution with high wear application:
  - Inserts
  - Glass filled staking
- Can be re-machined

Graphics: Branson Ultrasonics

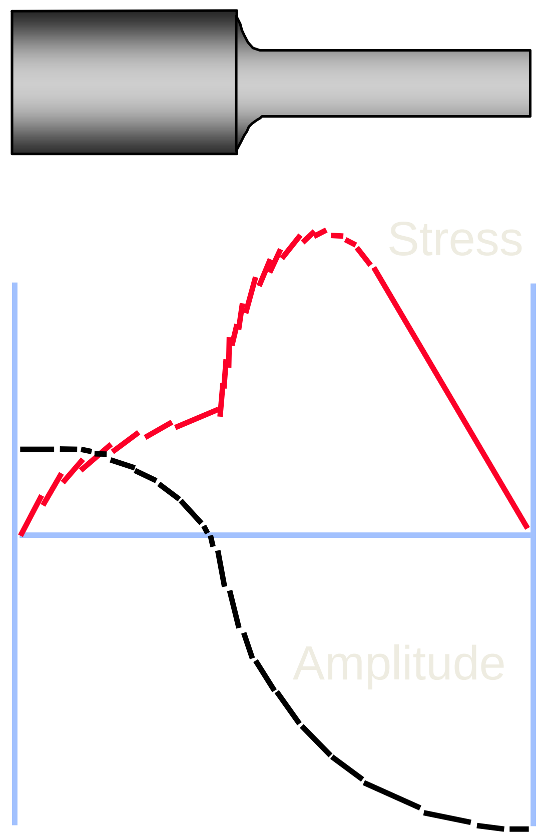
Horn design

- Three typical horns

Graphics: Branson Ultrasonics

Step horn

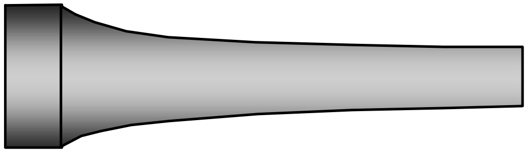
- Early design
- Moderate amplitude
- High stress
- Easy to manufacture

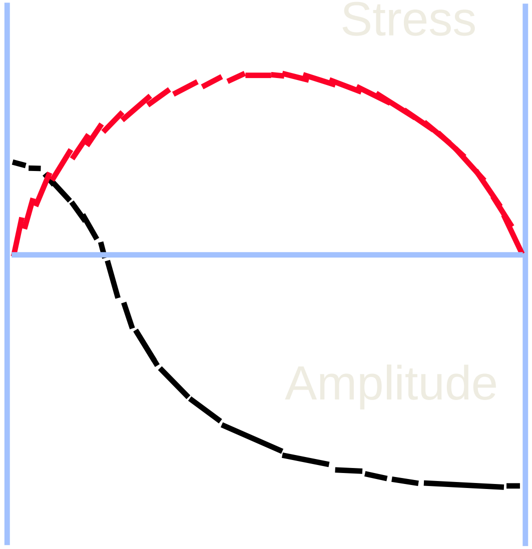


Graphics: Branson Ultrasonics

Exponential horn

- Moderate stress
- High amplitude

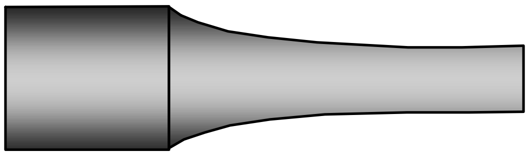


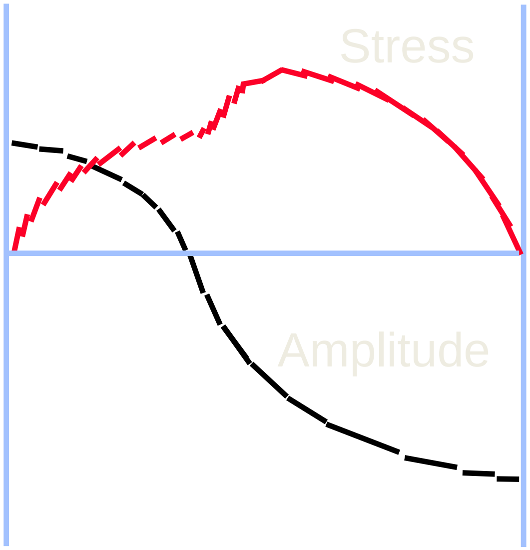


Graphics: Branson Ultrasonics

Catenoidal horn

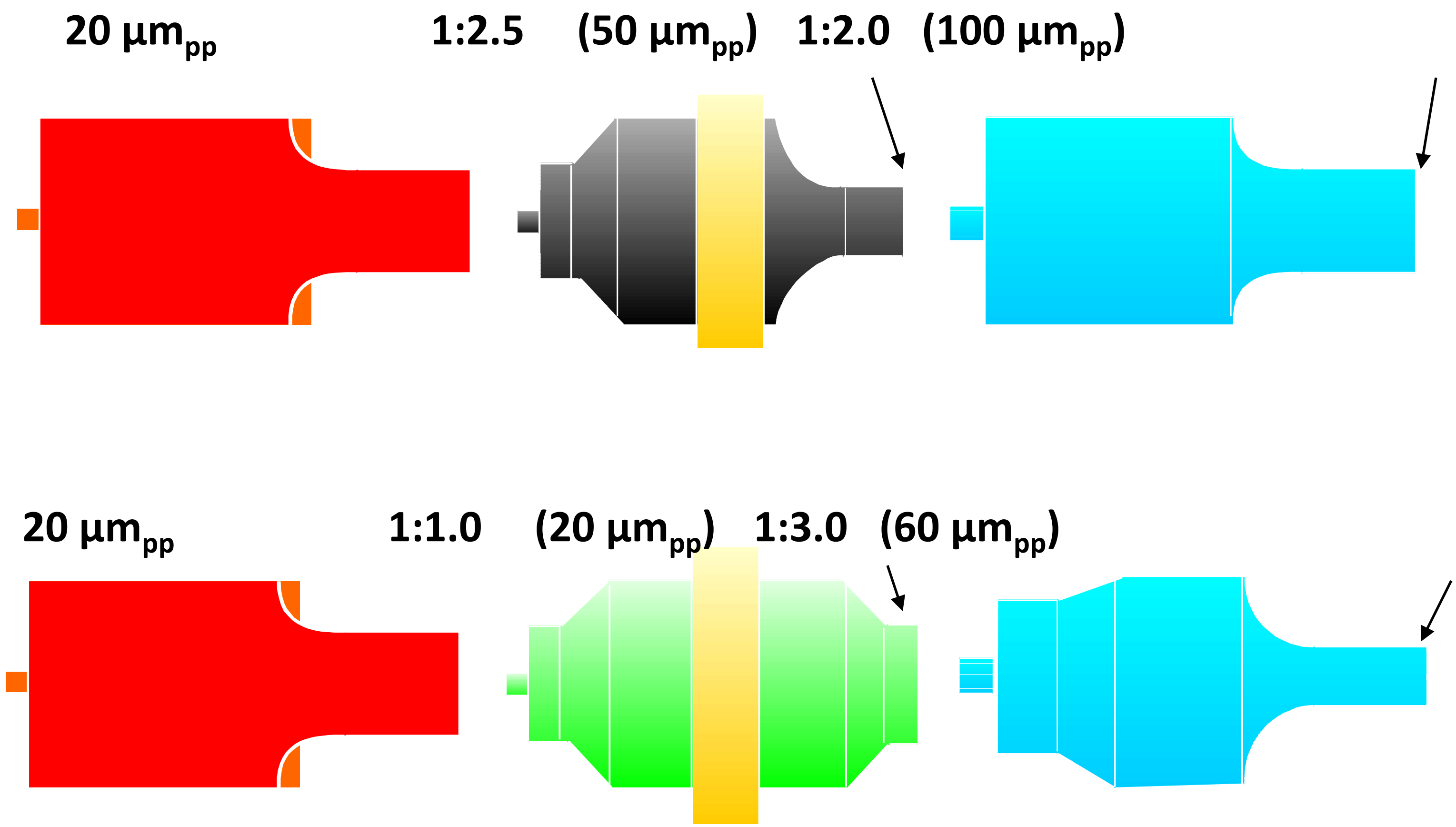
- Low stress
- High amplitude





Graphics: Branson Ultrasonics

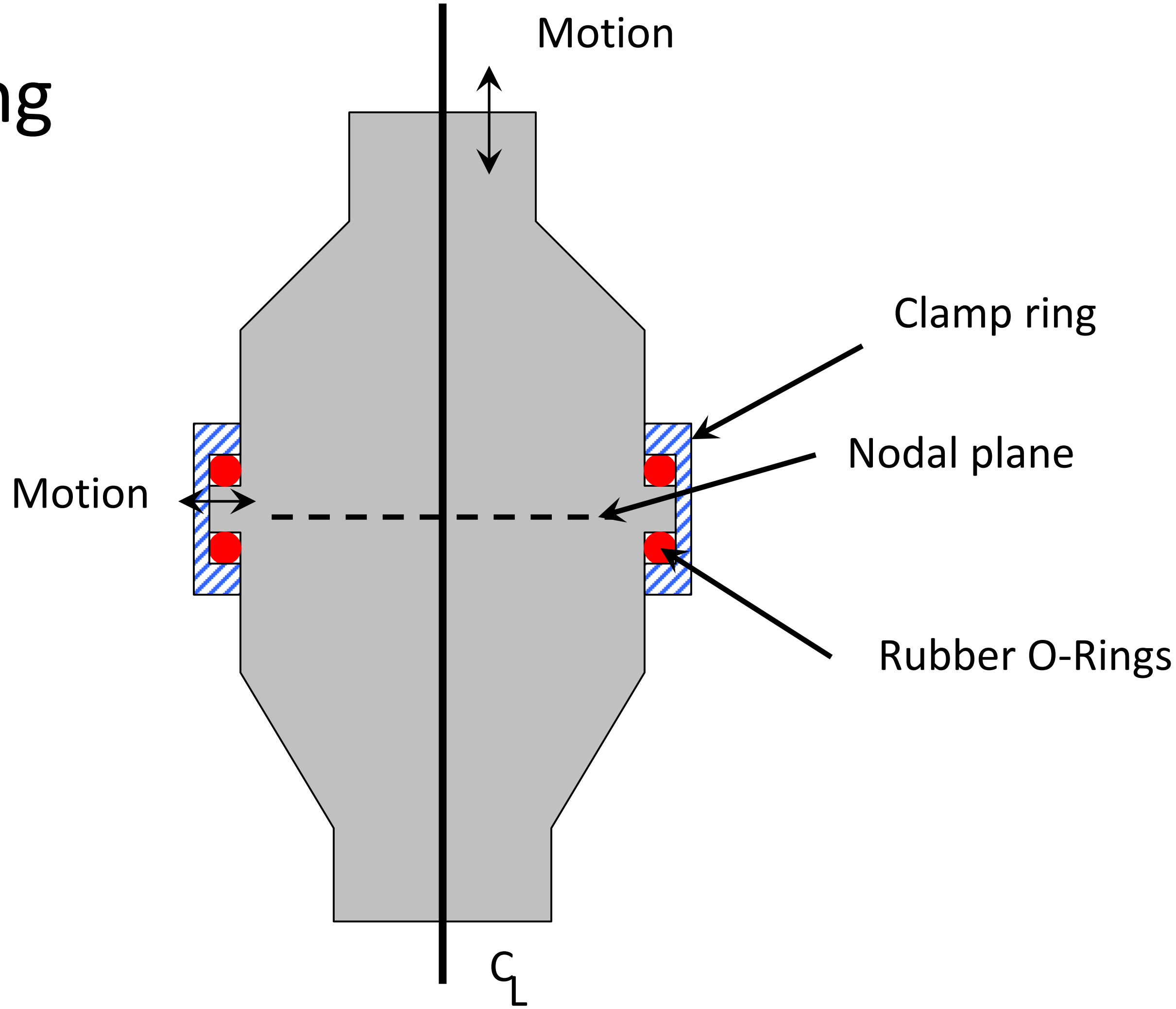
Stack amplitude:



Graphics: Branson Ultrasonics

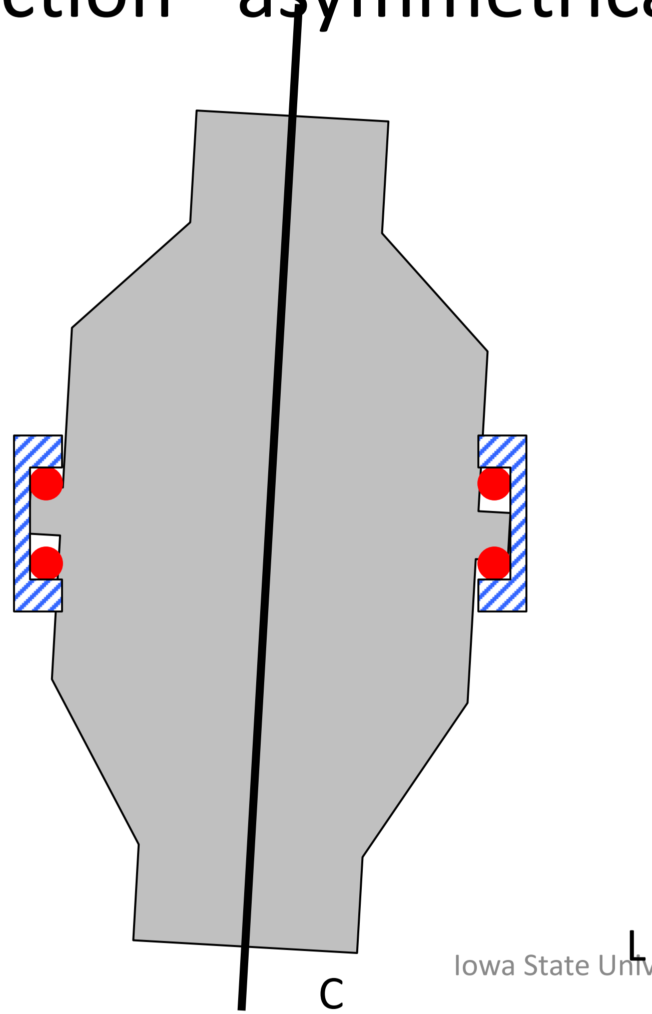
Booster

- Mounting



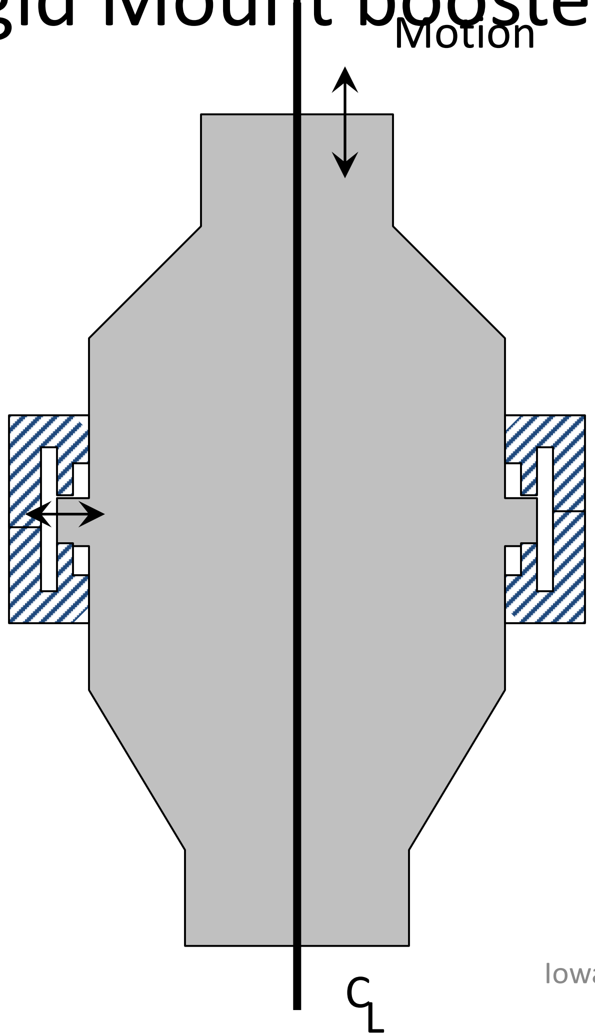
Booster

- Deflection –asymmetrical loading

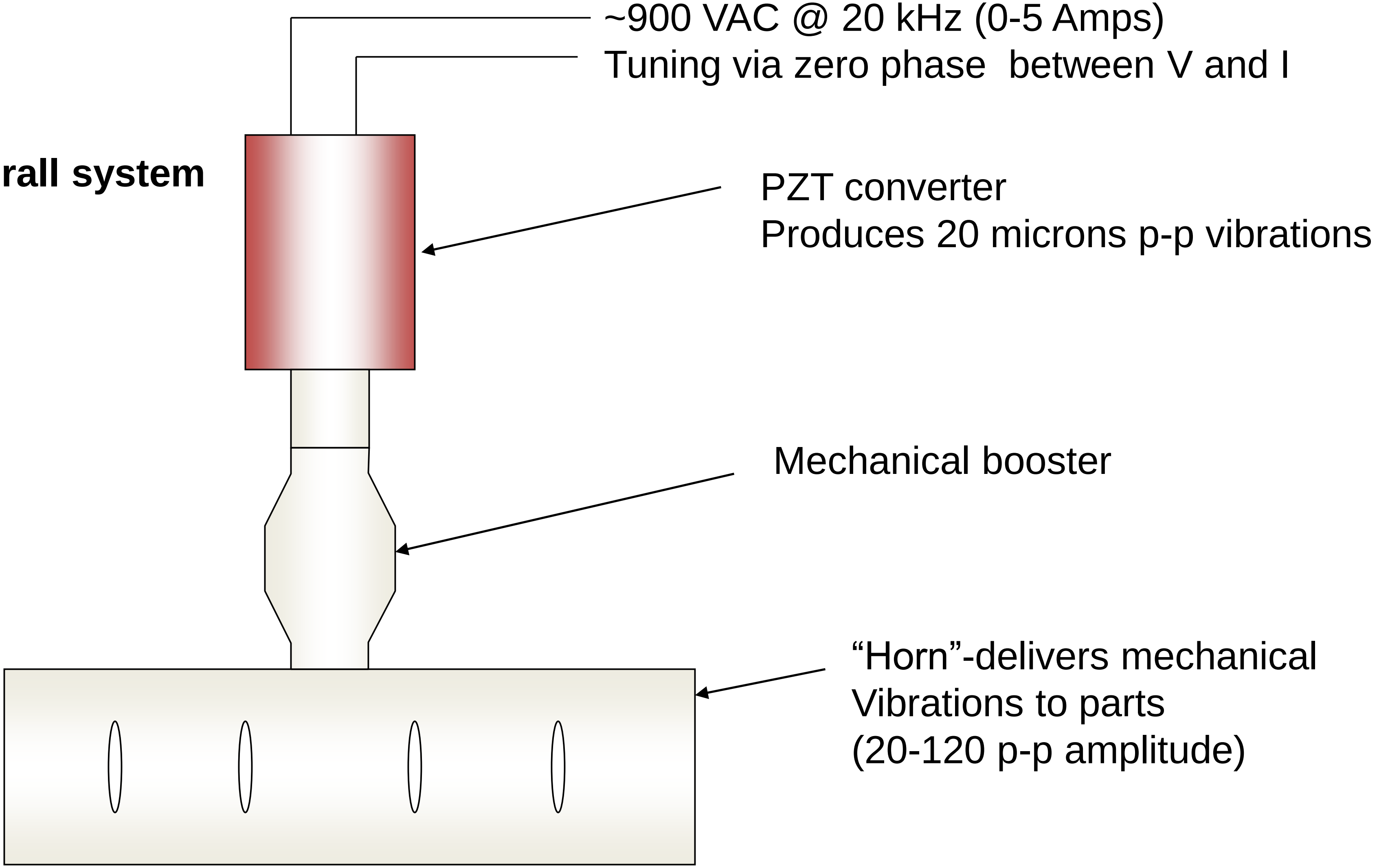


Booster

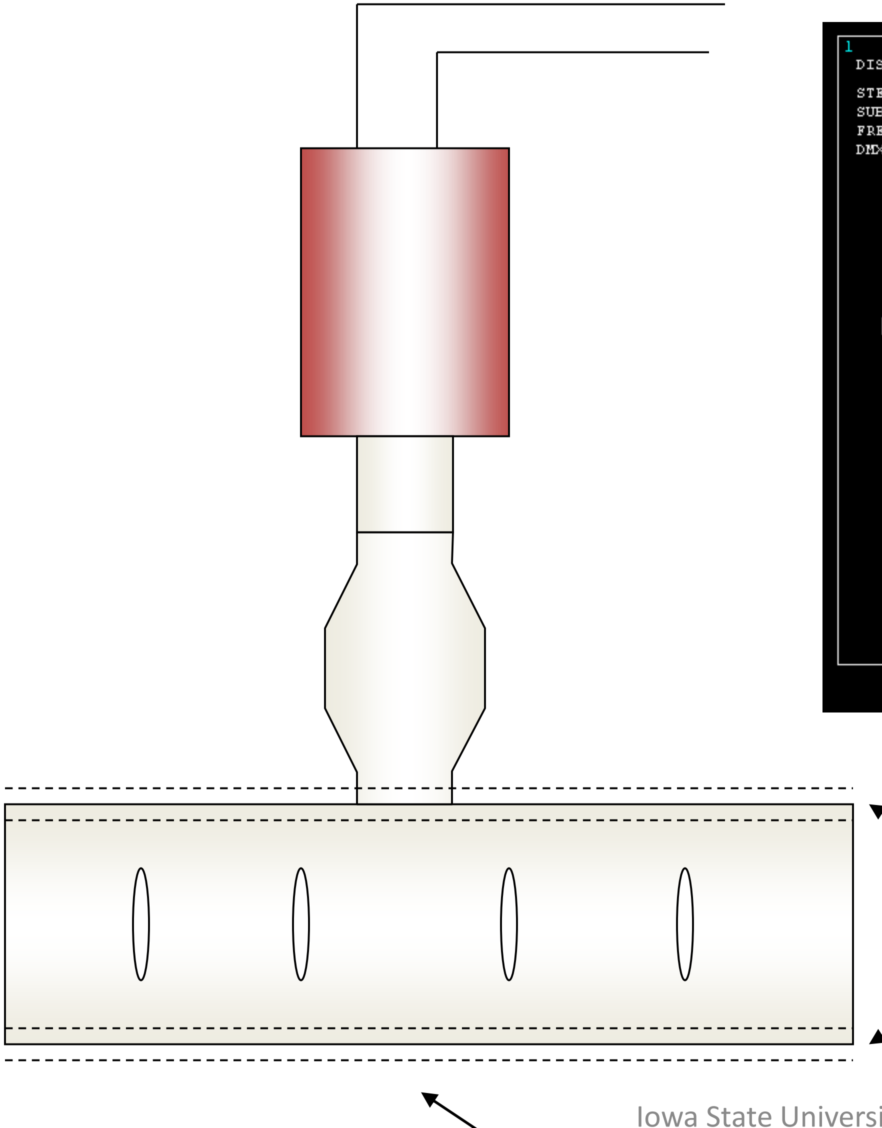
- Rigid Mount booster (converter)

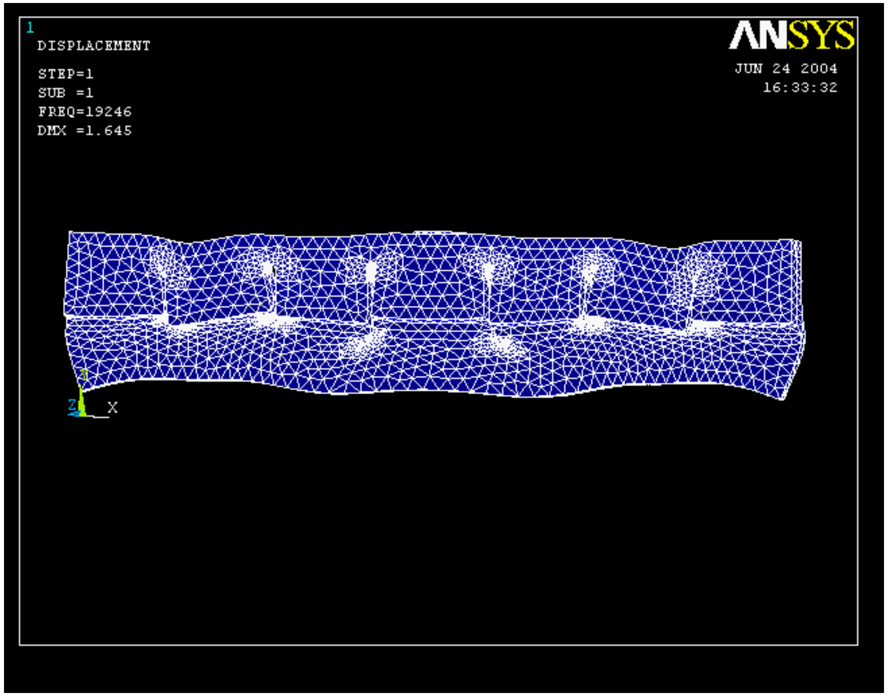


Overall system



Axial mode of vibration



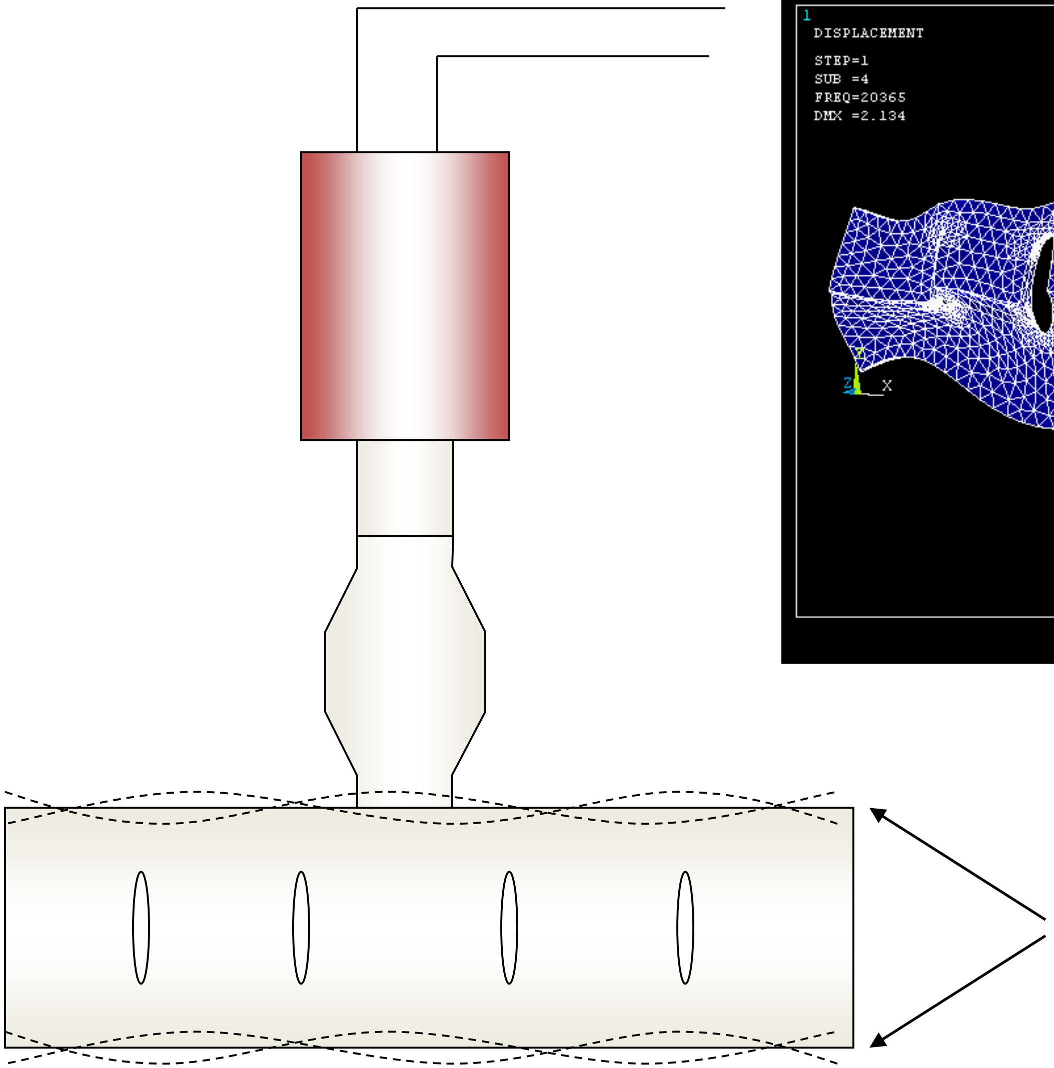


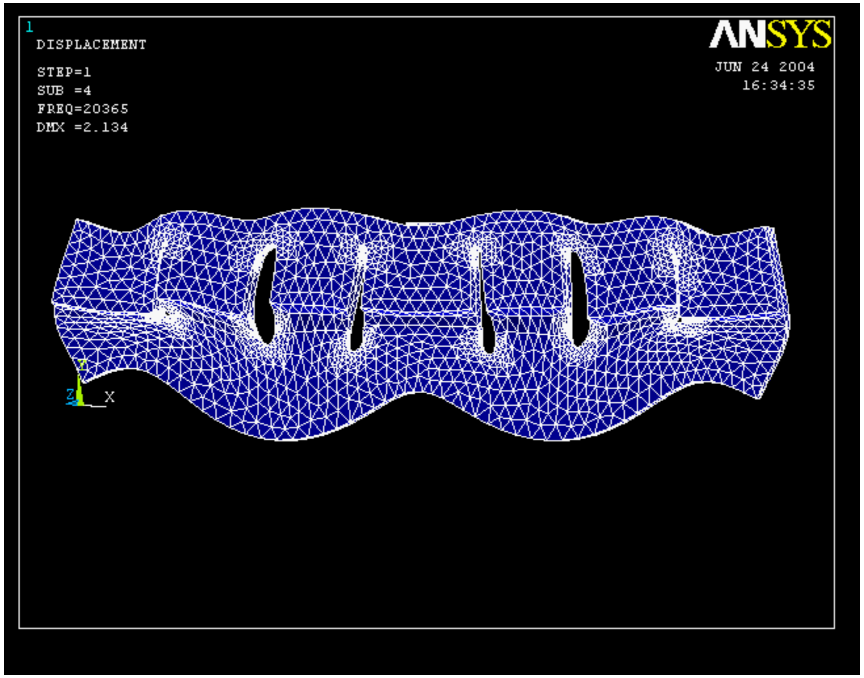
Ideal mode vibration

Uniform and in phase

Horn face that contacts part

Flexural mode of vibration





Possible flexural mode

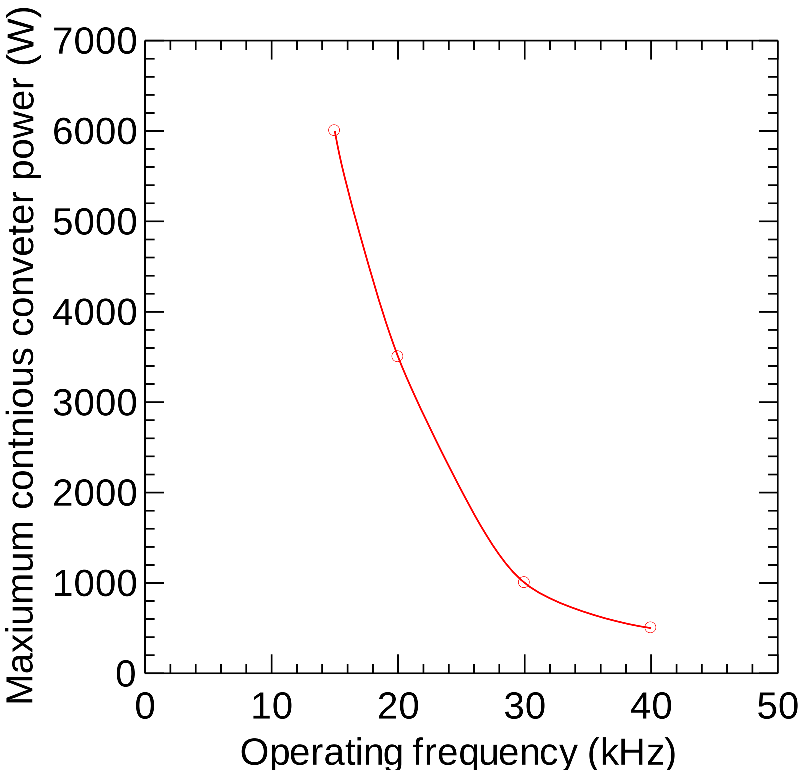
Ultrasonic frequencies

- Typical 20 and 40 kHz
- The higher the frequency the smaller the converter & stack
- Power is limited by converter capacity
- The power output is limited to size due to heat generation

Graphics: Branson Ultrasonics

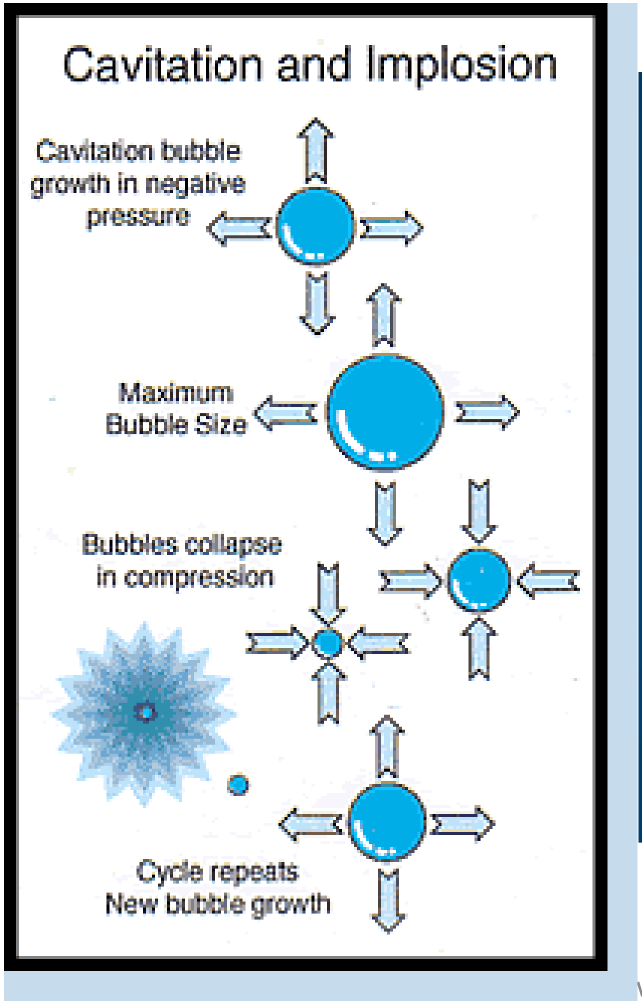
Ultrasonic frequencies

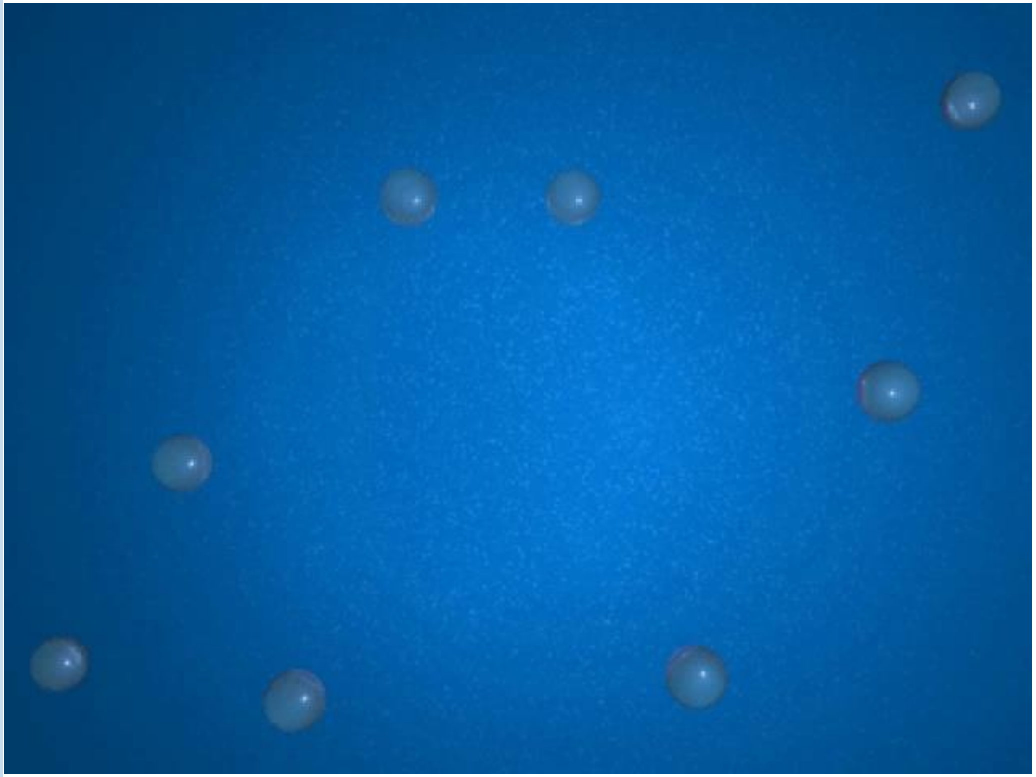
- Manufacturers rate converters by different duty cycles
- There is always some controversy on maximum power
- Typical max. power for a single converter (value vary for manufacturer):



Liquid processing

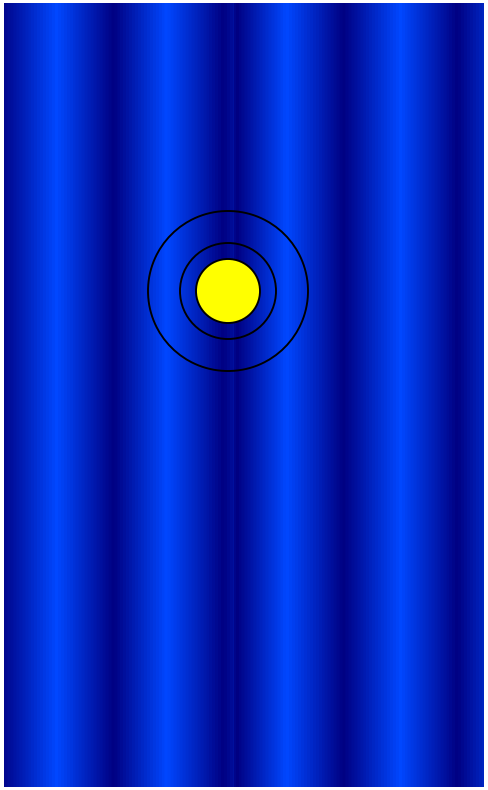
Cavitations

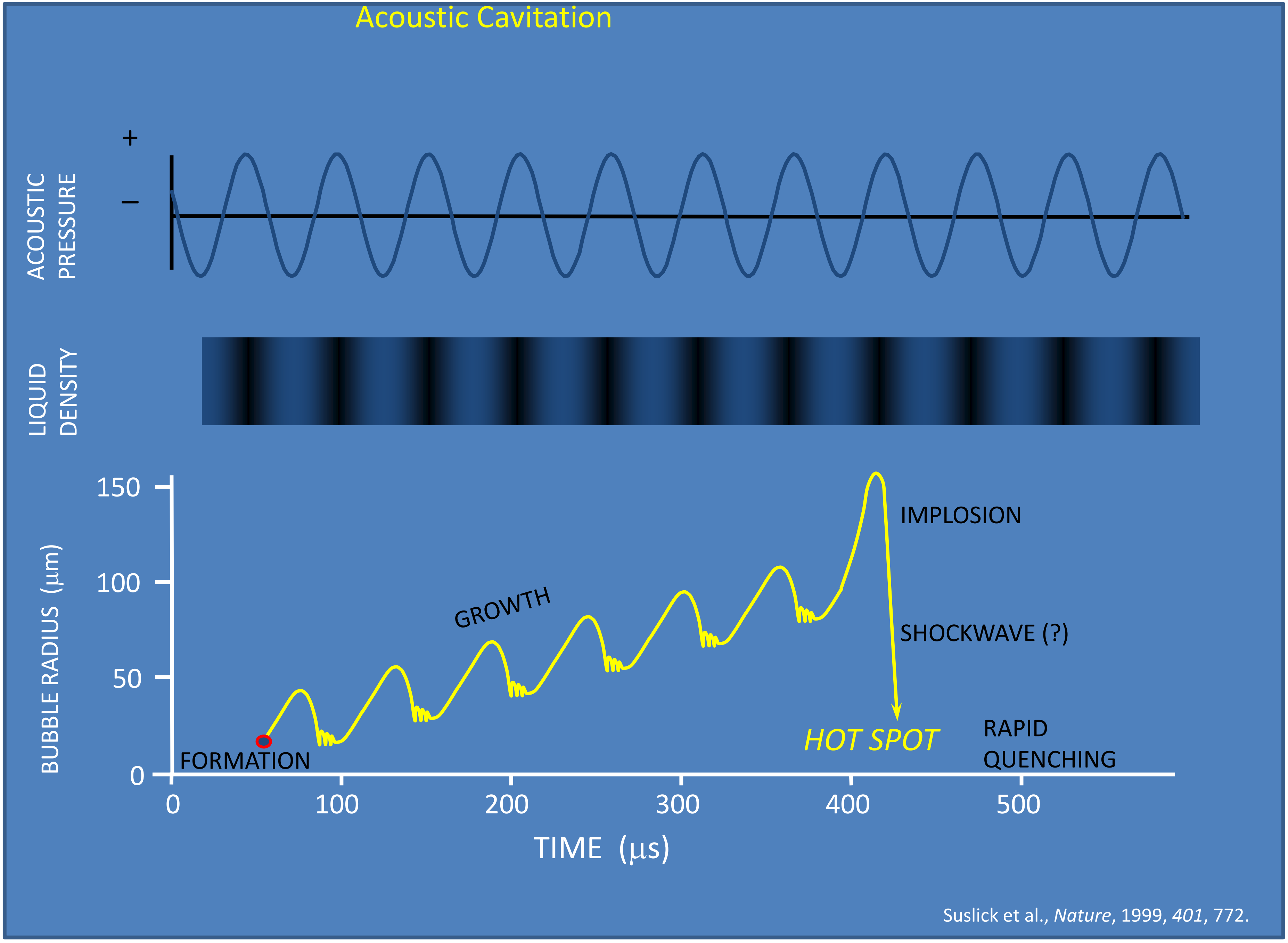




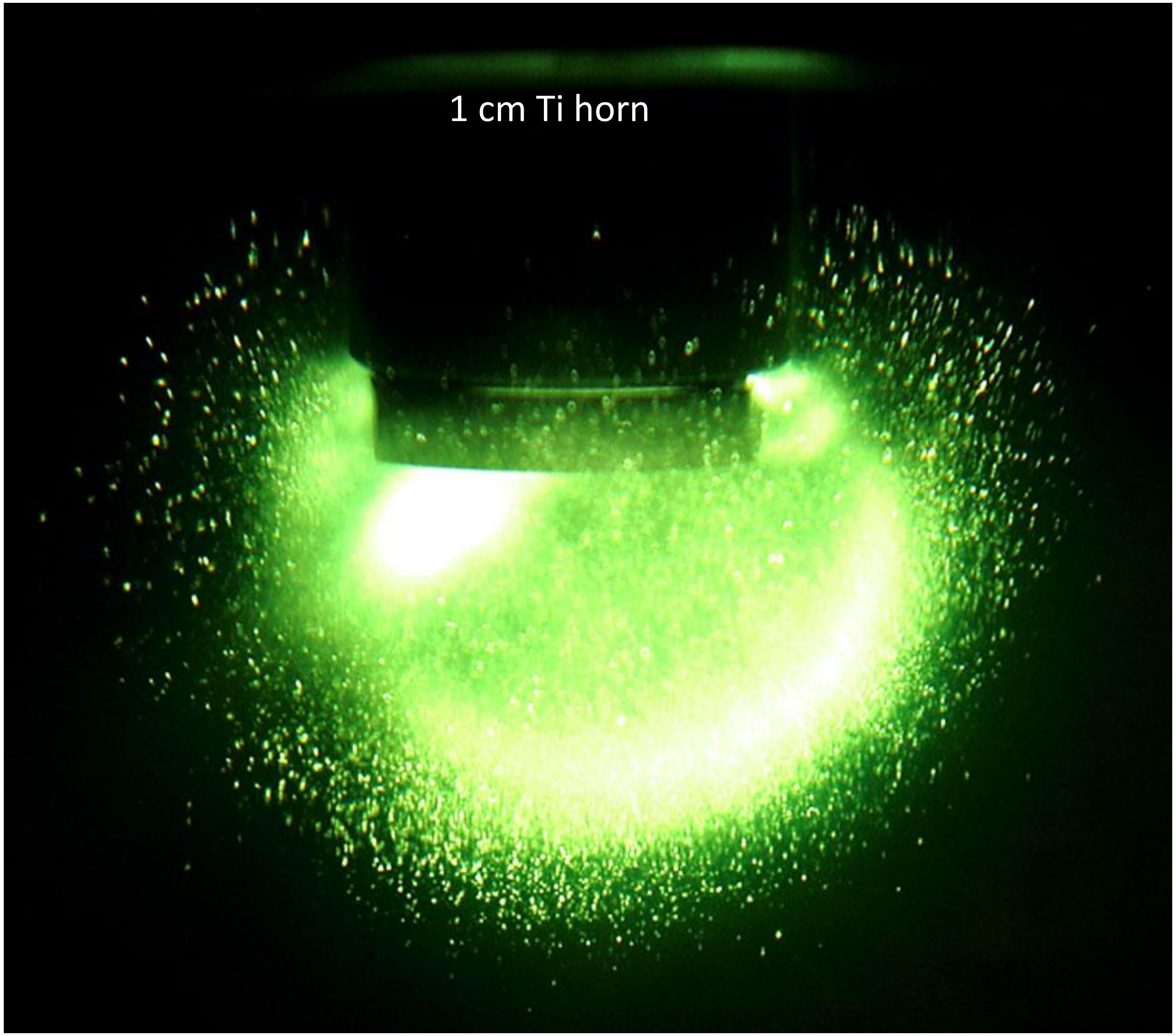
Sonics and Materials

Cavitation




Acoustic Cavitation
+
–
ACOUSTIC PRESSURE
LIQUID DENSITY
150
100
50
0
BUBBLE RADIUS (μm)
GROWTH
IMPLOSION
SHOCKWAVE (?)
HOT SPOT
RAPID QUENCHING
FORMATION
0
100
200
300
400
500
TIME (μs)
Suslick et al., Nature, 1999, 401, 772.

Multi-Bubble Sonoluminescence:



↕ 50 μm

Multibubble Cavitation:

Hot Spot Conditions in Bubble Clouds

Temperature:	5000 K
Pressure:	~300 atm
Duration:	~ 1 nsec
Cooling rate:	> 10^{12} K/sec

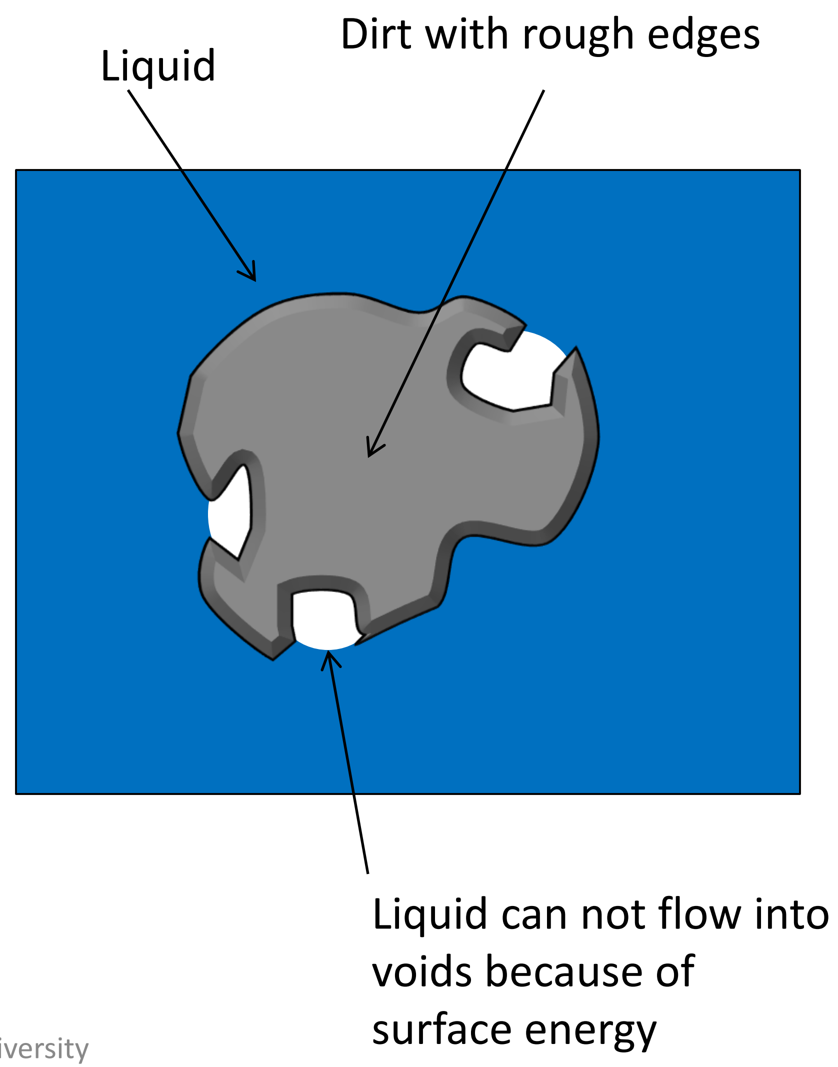
Suslick et al., *Nature*, 1999, *401*, 772.

Nucleation

- Without nucleation the cavitations process will not start without extremely high pressures
- The nucleation process acts a stress concentration point to cause tensile failure of the liquid (water =100 atms)
- Edges, dusts, etc
- Growth occurs when the local pressure (p) is less than the vapor pressure (p_v)

Nucleation

- Most often at:
  - Edge
  - Dust
  - Can be induced
    - Laser



Growth

- Cyclic growth
  - At high pressure the bubble decreases in size
  - At low (negative) pressure the bubble grows
  - The overall growth is positive

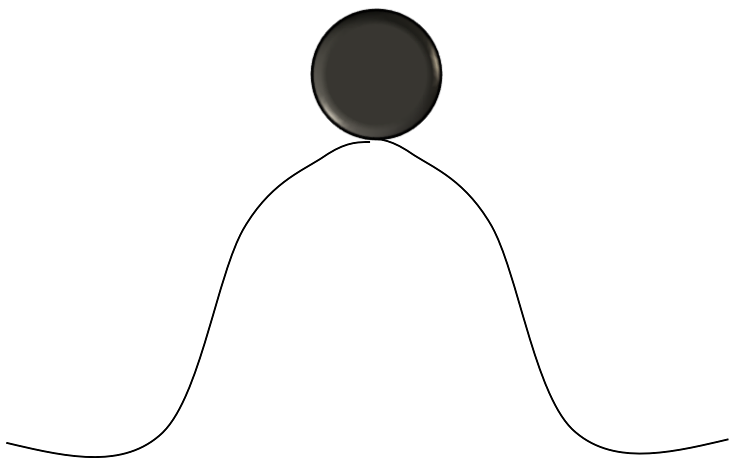
Rectified diffusion

- Once a bubble forms, the pressure change:
  - During compression the liquid near the bubble has increase saturation limit
    - Gas diffuses from the bubble into the liquid
    - The surface area is small because of compression
  - During rarefaction the liquid becomes super saturated
    - Gas diffuses from the liquid into the bubble
    - The surface area is large
  - The relative change in surface area causes more gas into the bubble overtime

Collapse

- This is similar to buckling issues
  - Blowing a bubble that is too large
  - Soap bubble too large

Stable



Un-stable

Collapse

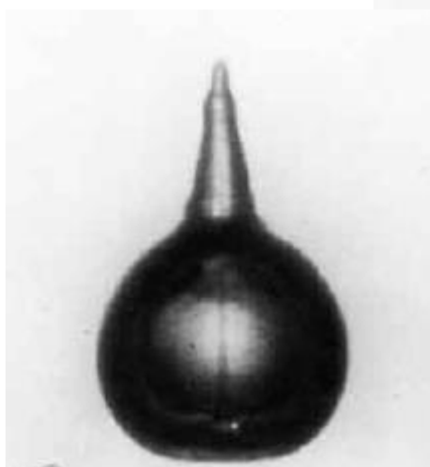
- Isothermal
  - High surface area to volume ratio
  - As bubble collapses the gas in compressed
  - Not until the very last moment does the temperature climb
  - 5000 K

Collapse

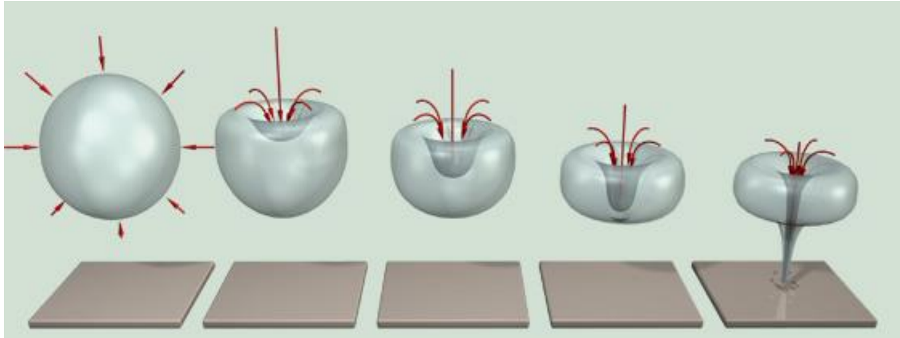
Asymmetrical collapse

- Near by forces
  - Particle
  - Bubbles
  - Temperature
  - Pressure
  - etc

Jetting

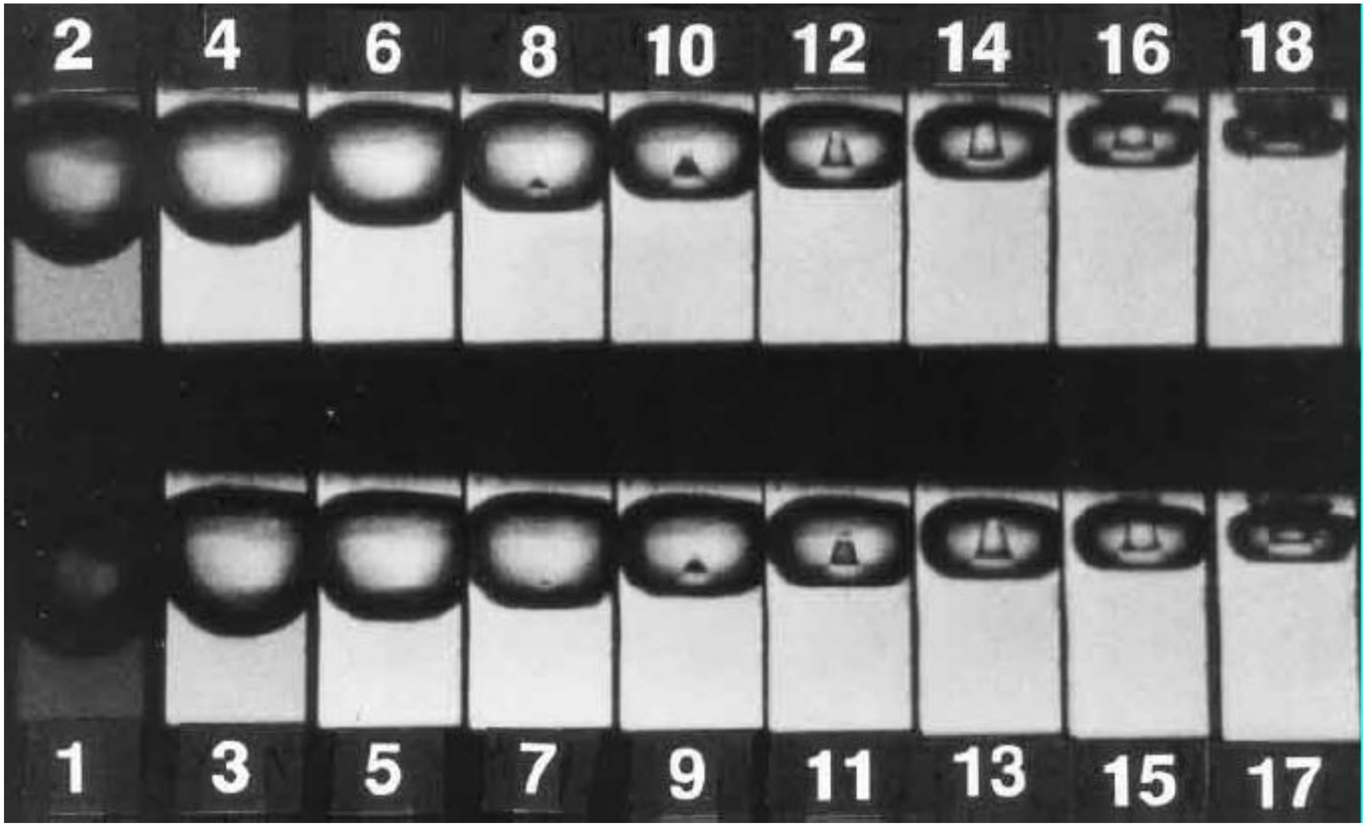


Collapse

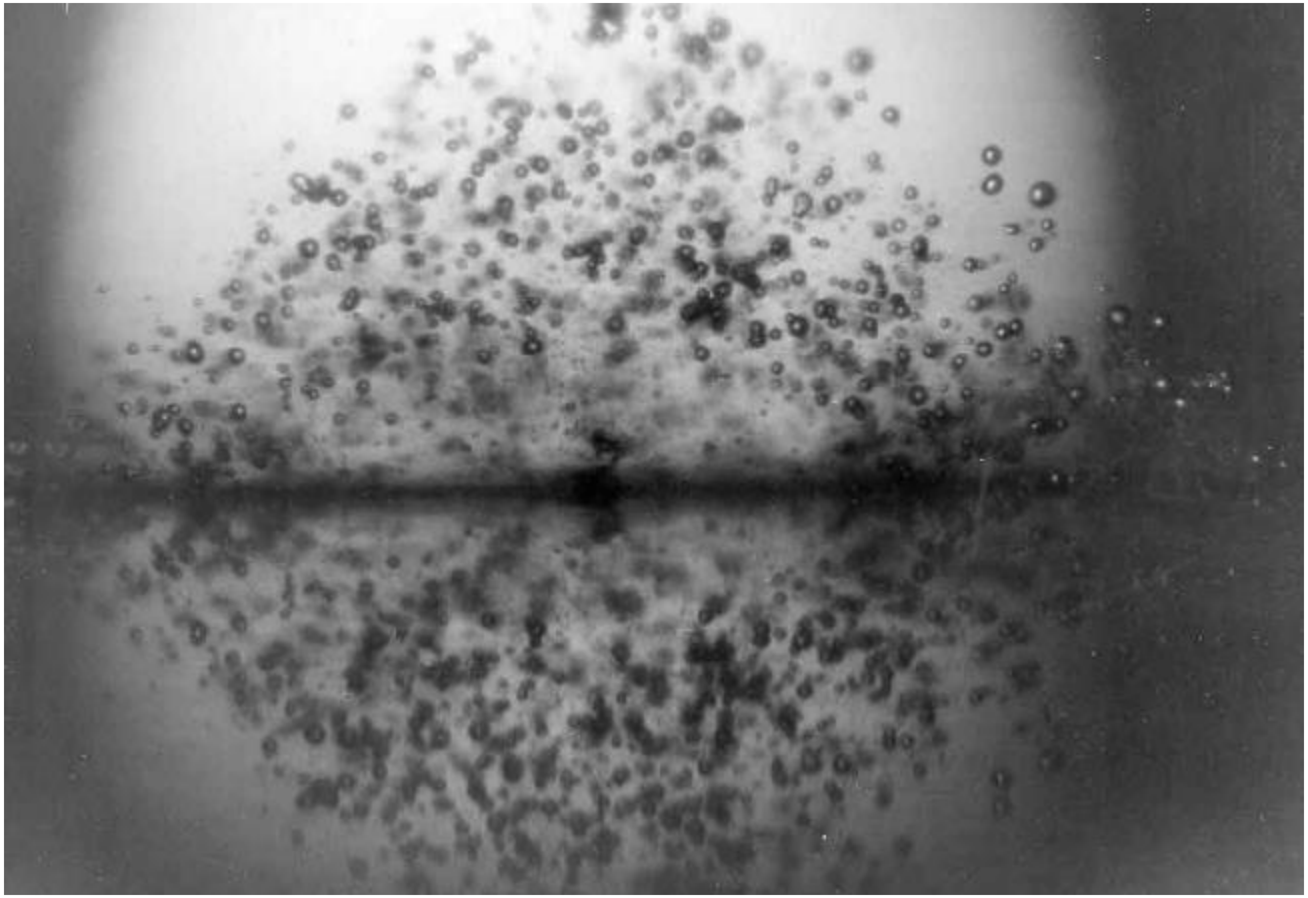


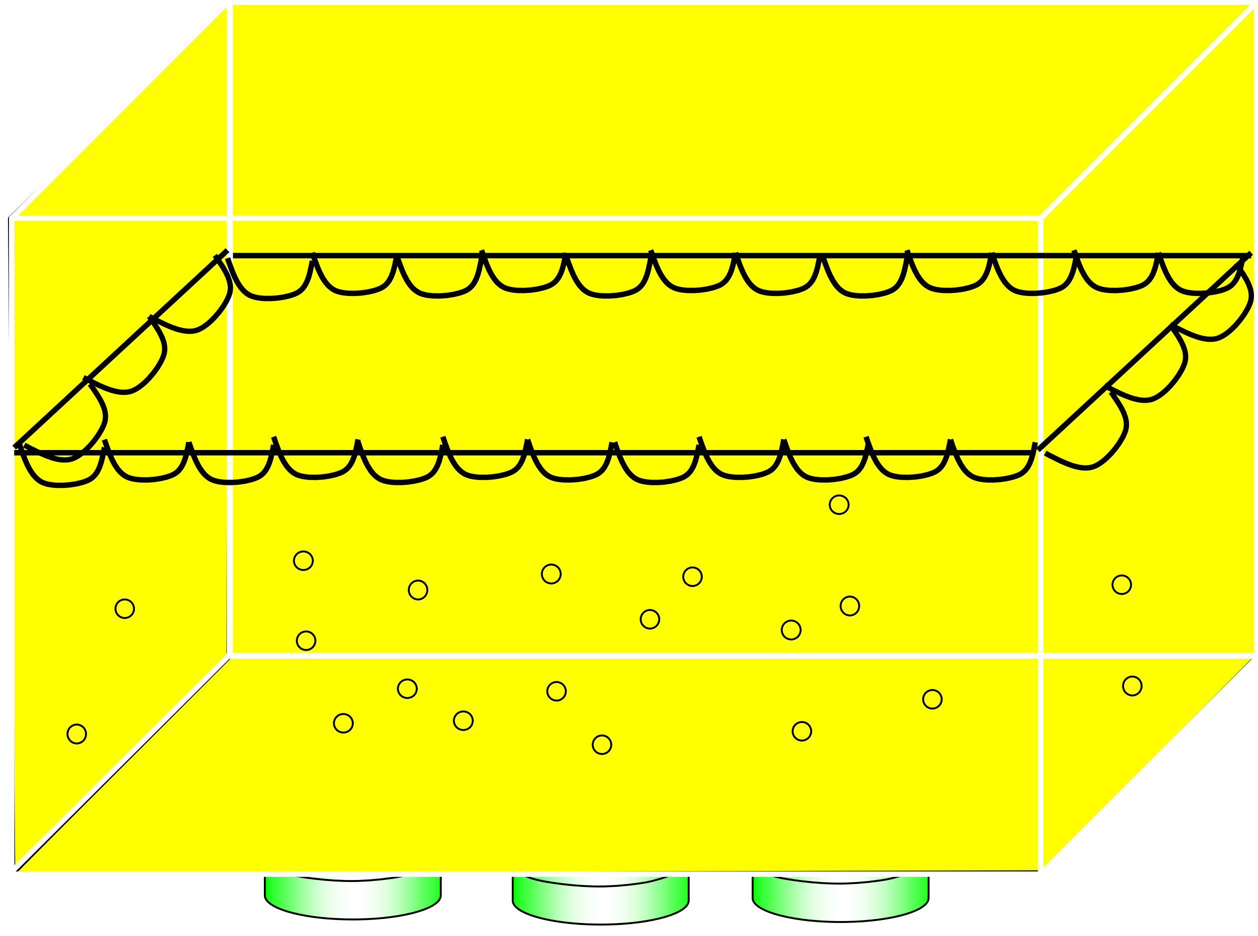
Storz doulth shock wave : web image for Ultrasonic shock wave therapy equipment.
(http://www.lockstockuae.com/products/_storz_duolith_shockwave) visited on 5/13/2011

Propagation



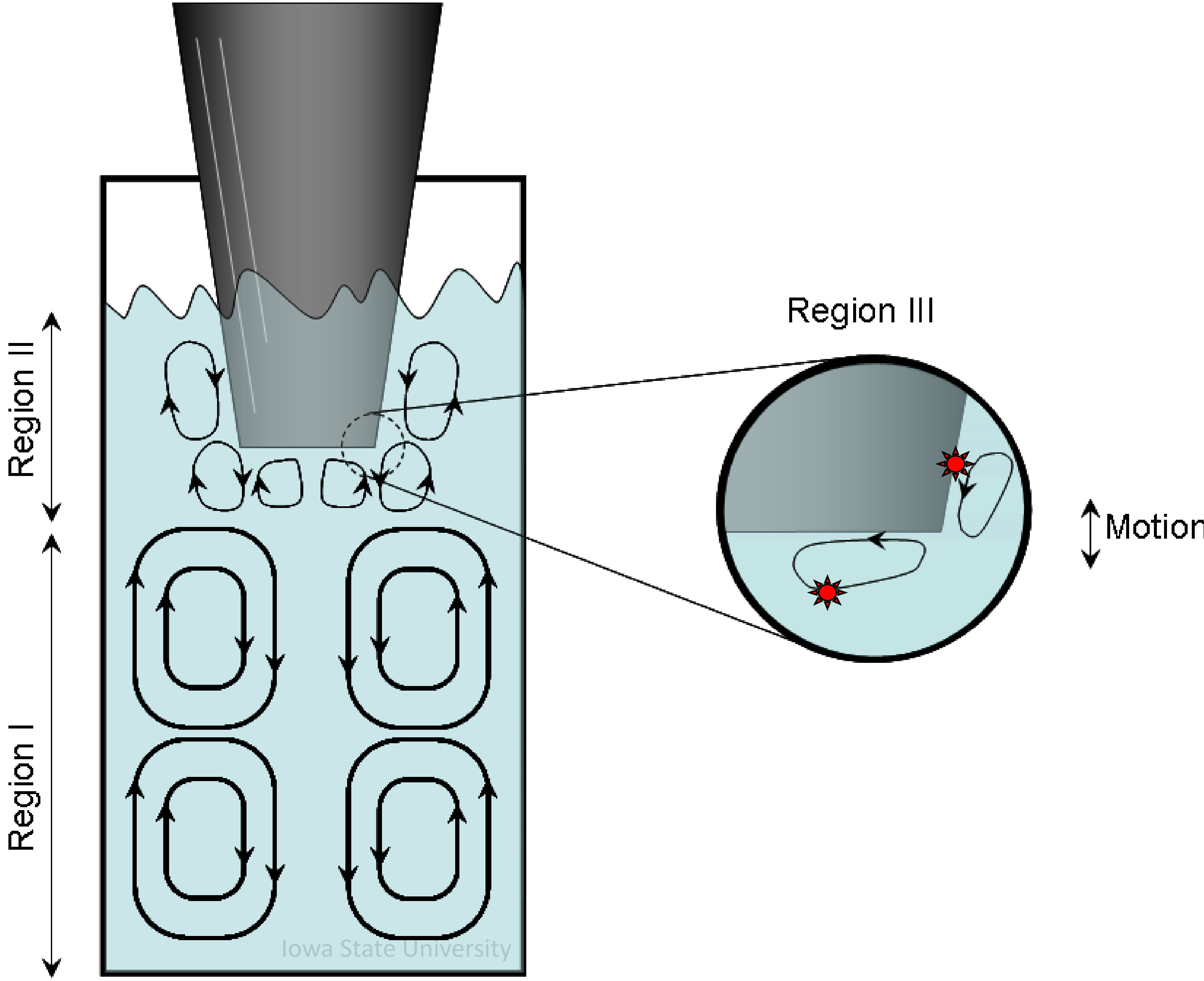
Propagation



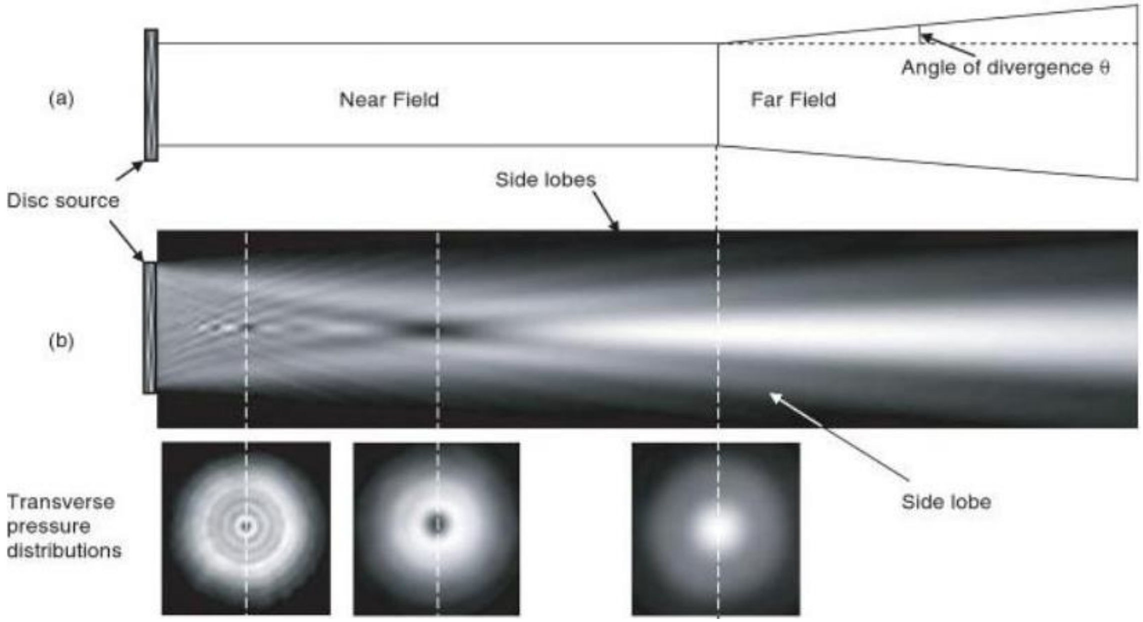


Liquid processing

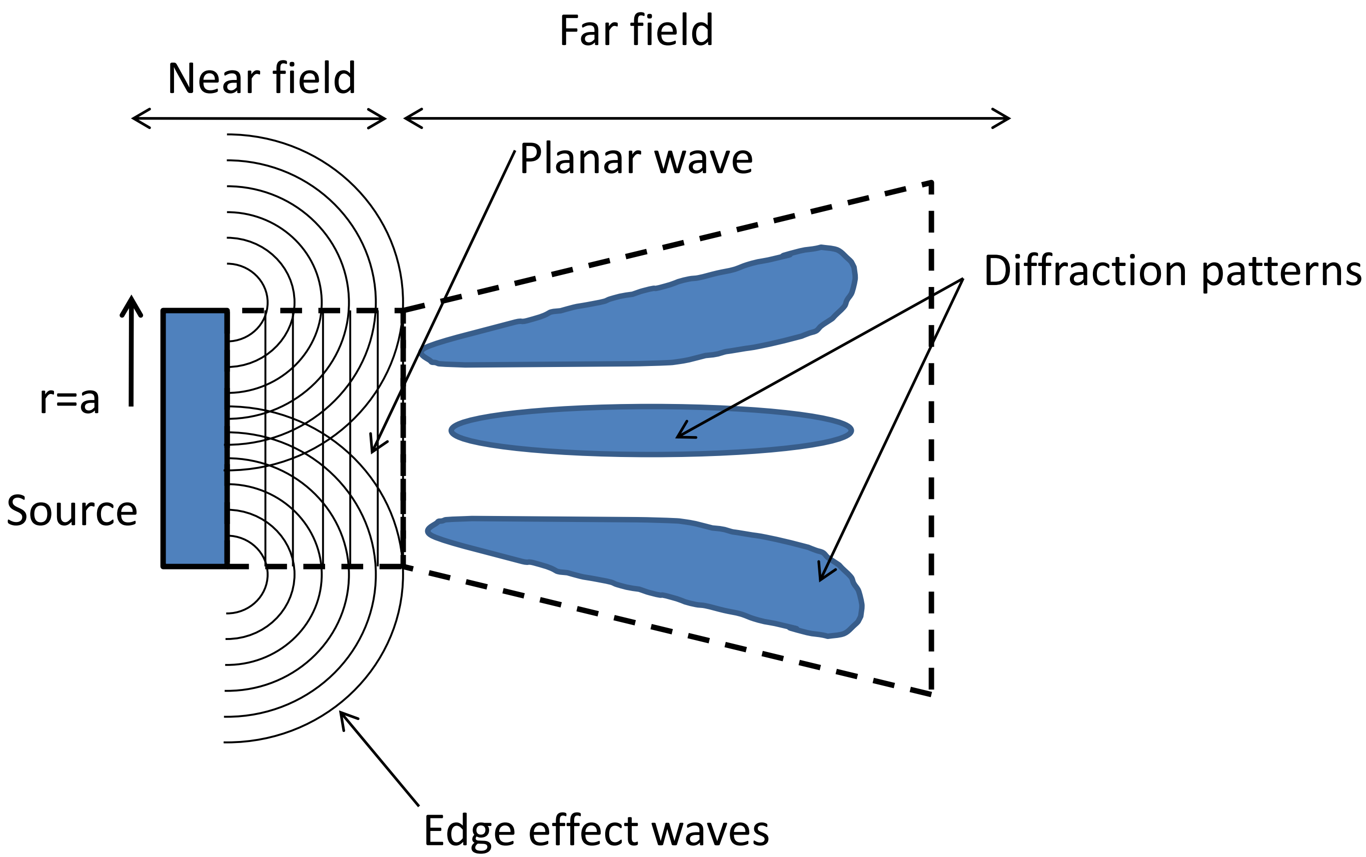
Streaming



Far field vs near field

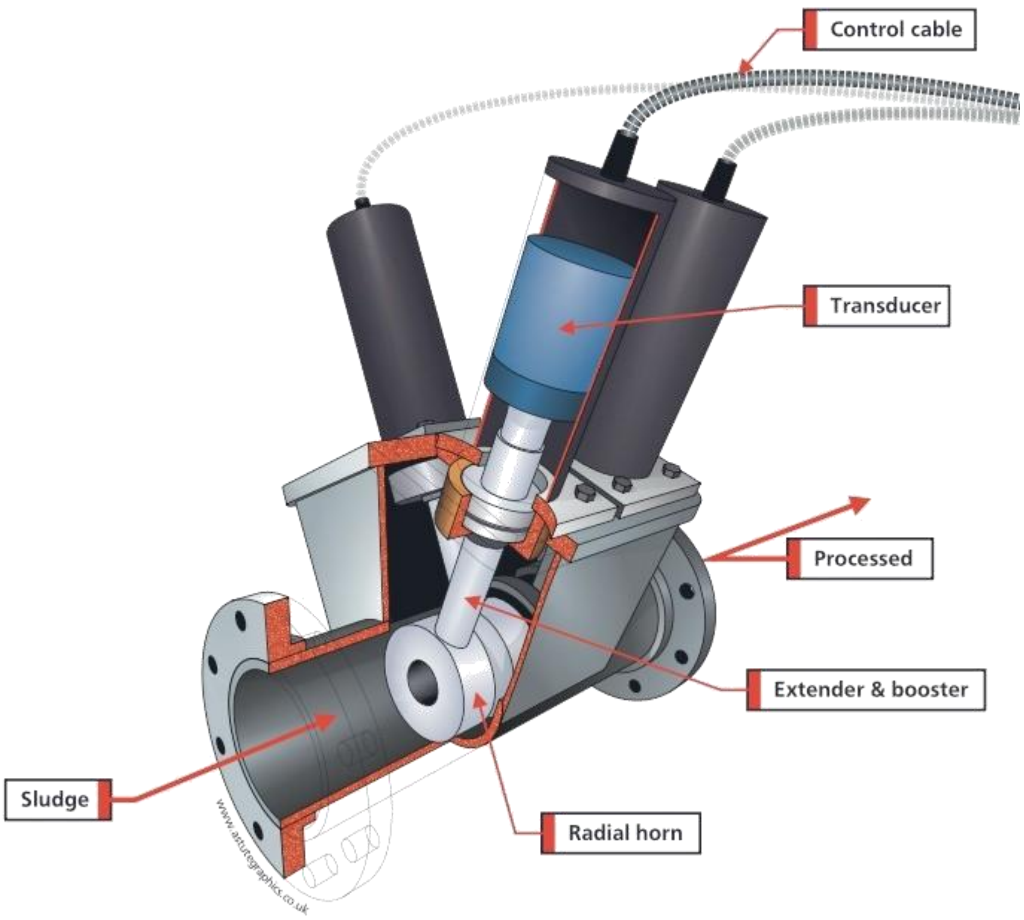


Far field vs near field

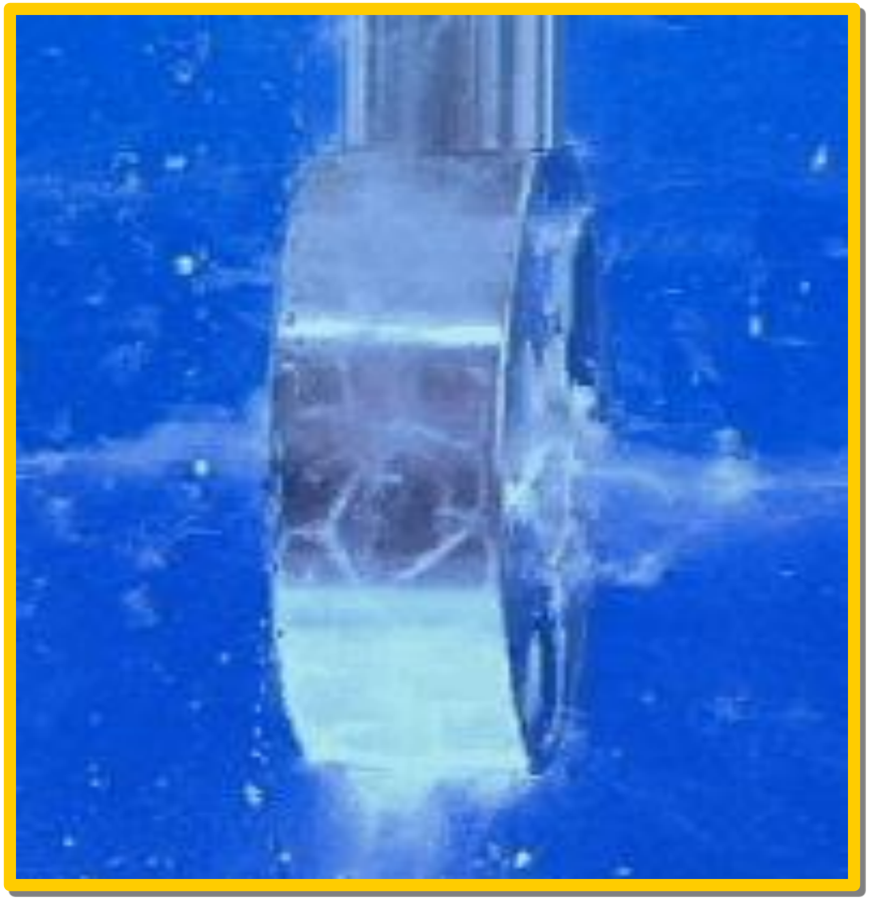


$R = \pi a^2/\lambda$

Continues treatment



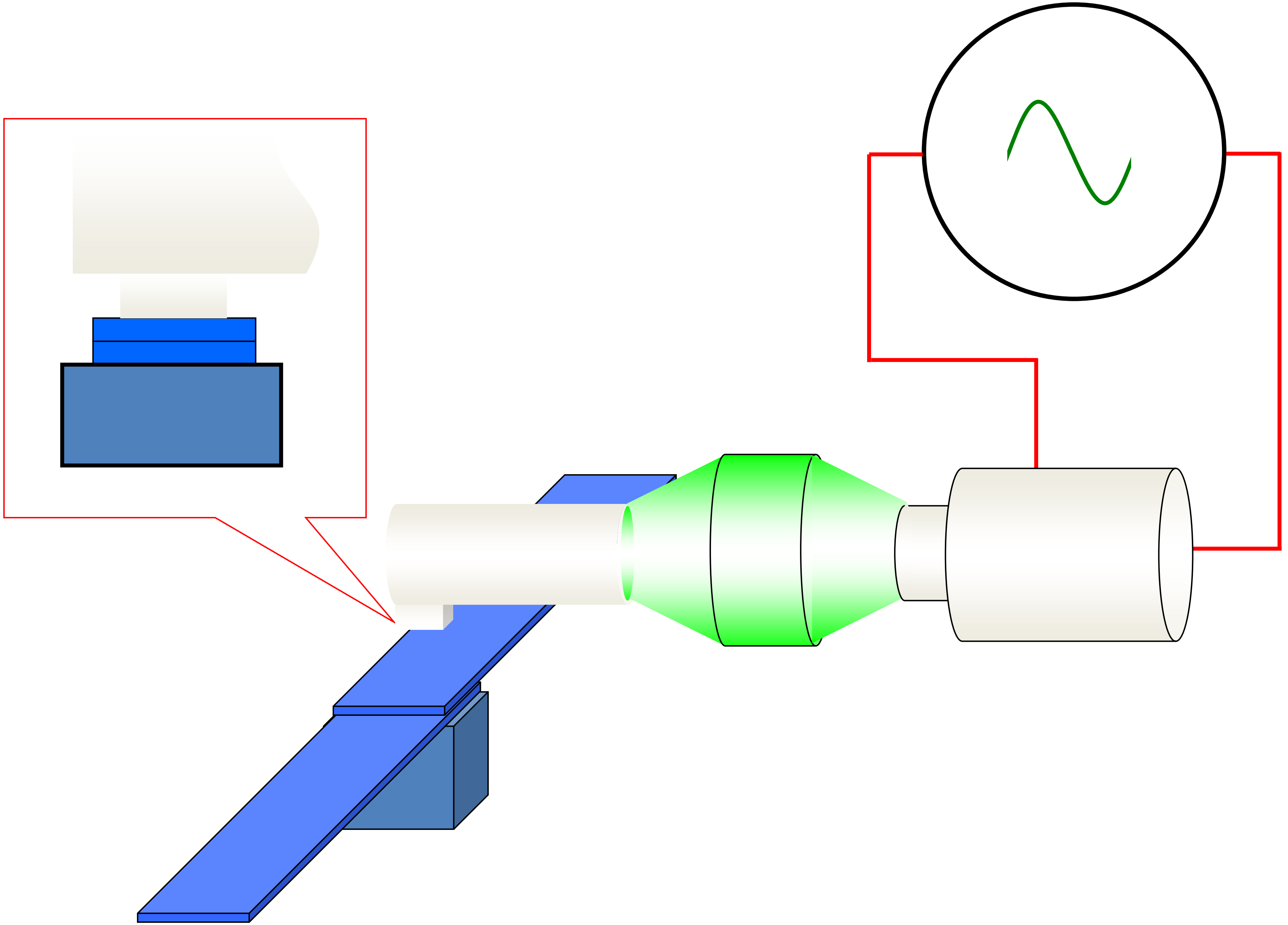
Continues treatment



Branson Ultrasonics

Applications

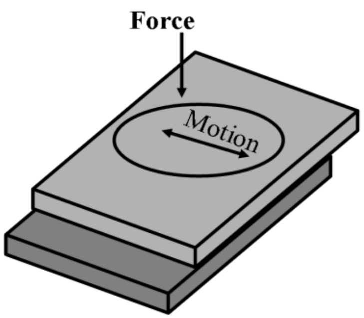
- Industrial
  - Metal welding
  - Plastics welding
  - Cutting
  - Drilling
- Bio
  - Biofuels
  - Medical

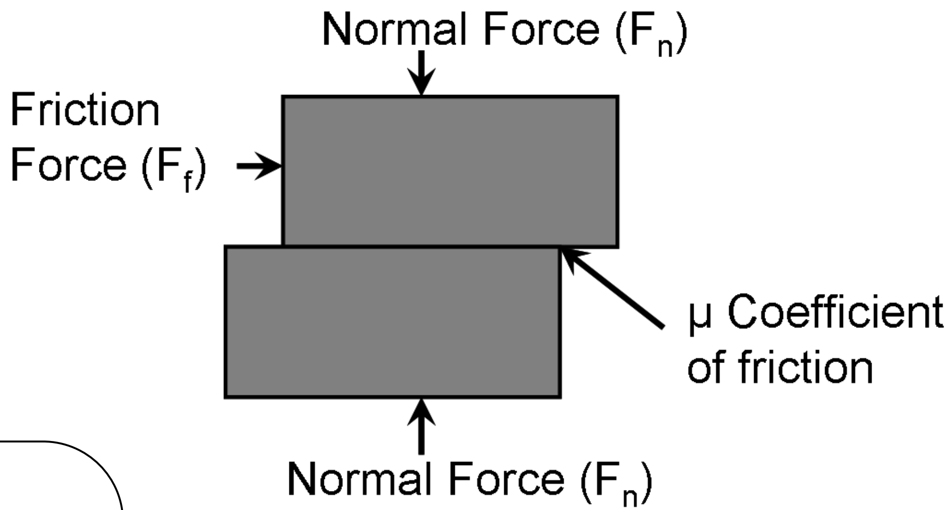


Iowa State University

Frictional heating

Theoretical Stokes Model





Model assumptions:

1. No losses on motion with the sample
2. The lower part remains perfectly stationary
3. Constant material properties
4. Constant displacement and forces
5. No inertial effects
6. No stored energy

Frictional heating

- Power –defined as:

$$P = F \bullet v$$ F -frictional force; v –velocity

- Instantaneous velocity –defined as:

$$v(t) = A_0 \omega \sin(\omega t)$$

- Instantaneous displacement –defined as:

$$x(t) = -A_0 \cos(\omega t)$$ A_0 – peak displacement

Frictional heating

- Instantaneous dissipated power –defined as:

$$P(t) = F \bullet A_0 \omega \sin(\omega t)$$

- Frictional force –defined as:

μ -coefficient of friction;

$$F = \mu \cdot f$$

f –applied normal force

- Instantaneous power –redefined as:

$$P(t) = f \mu A_0 \omega \sin(\omega t)$$

Frictional heating

- The average Power –estimated by integrating the previous function over a wave period –defined as:

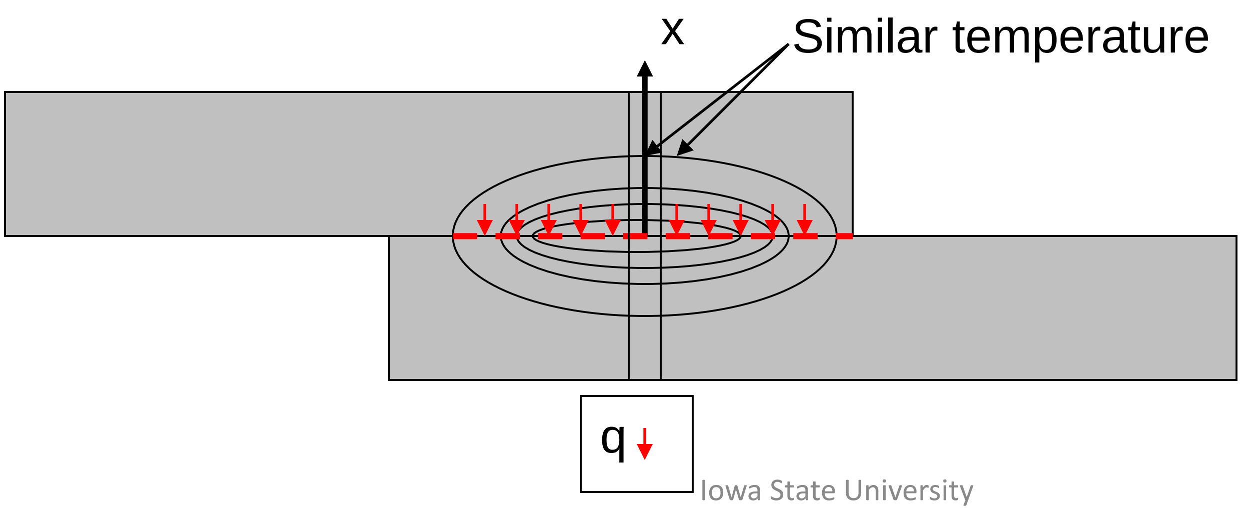
$$P_{avg} = \frac{2 f \mu A_0 \omega}{\pi}$$

Frictional heat

Additional assumptions:

- Amplitude at the weld interface - approximately 50% of the prescribed amplitude

-1-D heat flow (only concerned about peak temp)



Heating

- To estimate bond line temperature – a semi infinite one dimensional model – assumed

$$\theta(x,t) = \theta_i + \frac{2\cdot \dot{q}_0}{\lambda}\left[\sqrt{\frac{\kappa\cdot t}{\pi}}\cdot \exp\left(-\frac{x^2}{4\cdot\kappa\cdot t}\right) - \frac{x}{2}\cdot \operatorname{erfc}\left(\frac{x}{2\sqrt{\kappa\cdot t}}\right)\right]$$

θ–temperature,

x –position,

t –time,

θ_i –initial temperature of the solid,

q_0 –heat flux at the surface,

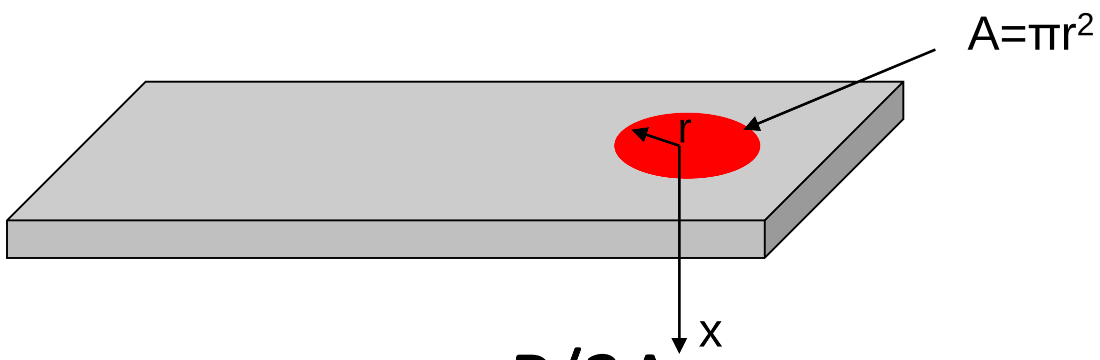
λ –thermal conductivity,

κ –thermal diffusivity (λ/ρC),

erfc (z) –complementary error function

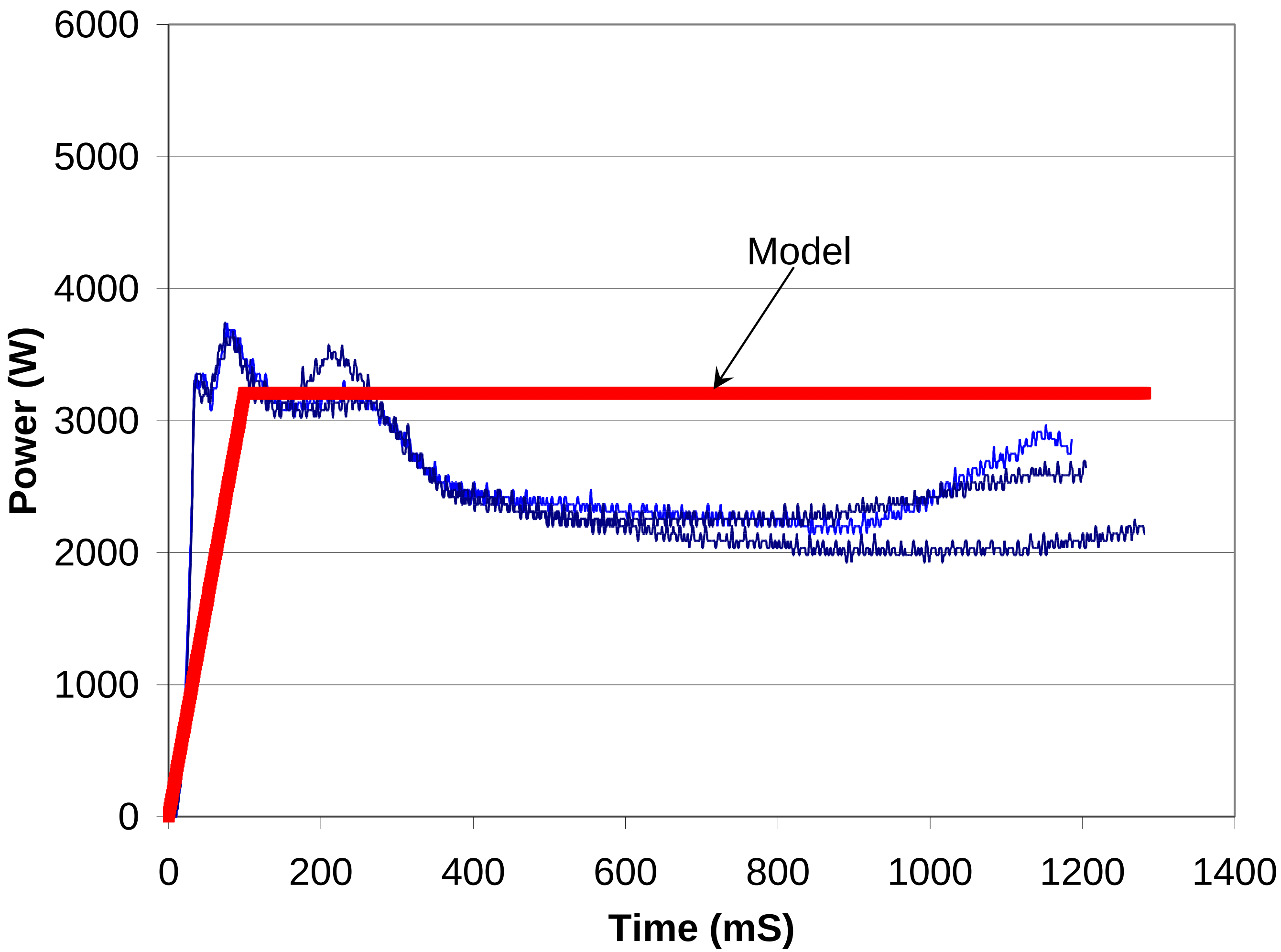
Heating

- Consider only the final size of the weld
- Estimate the weld failure area
- Estimate the heat flux at the surface (x=0)

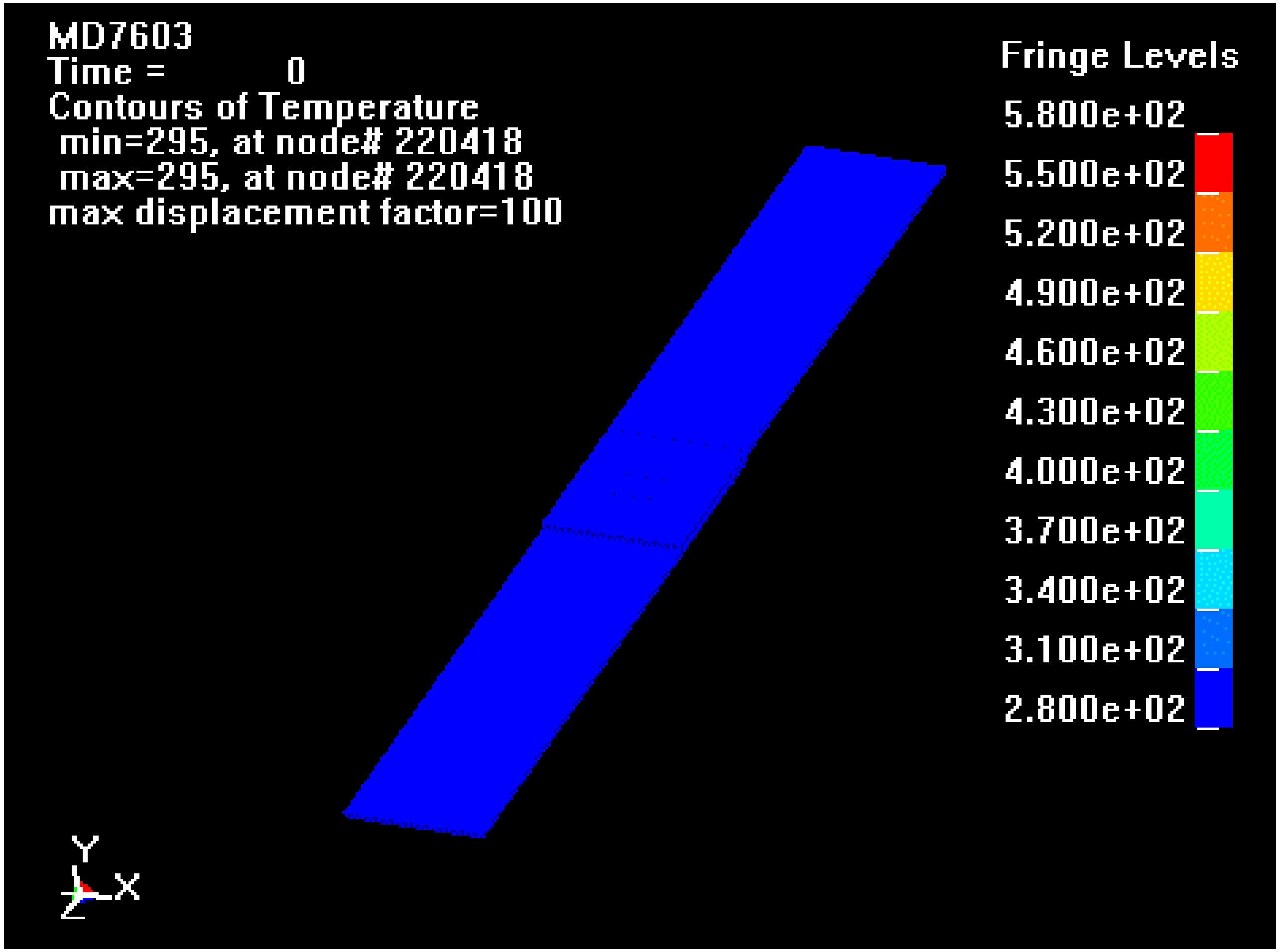


$$q_0 = P/2A$$

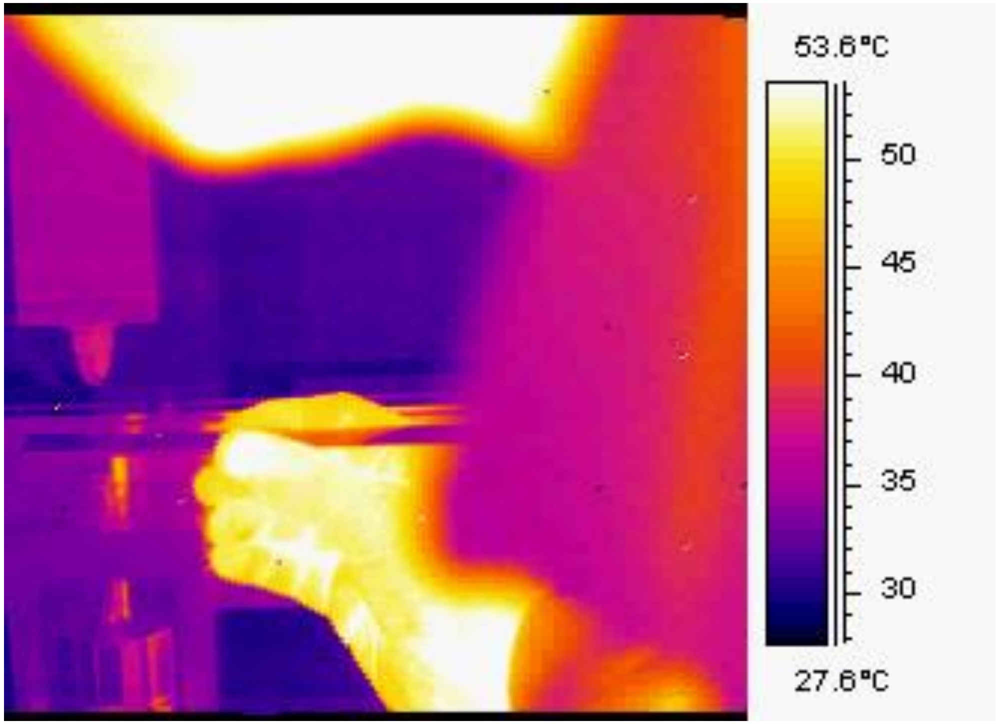
Frictional heating



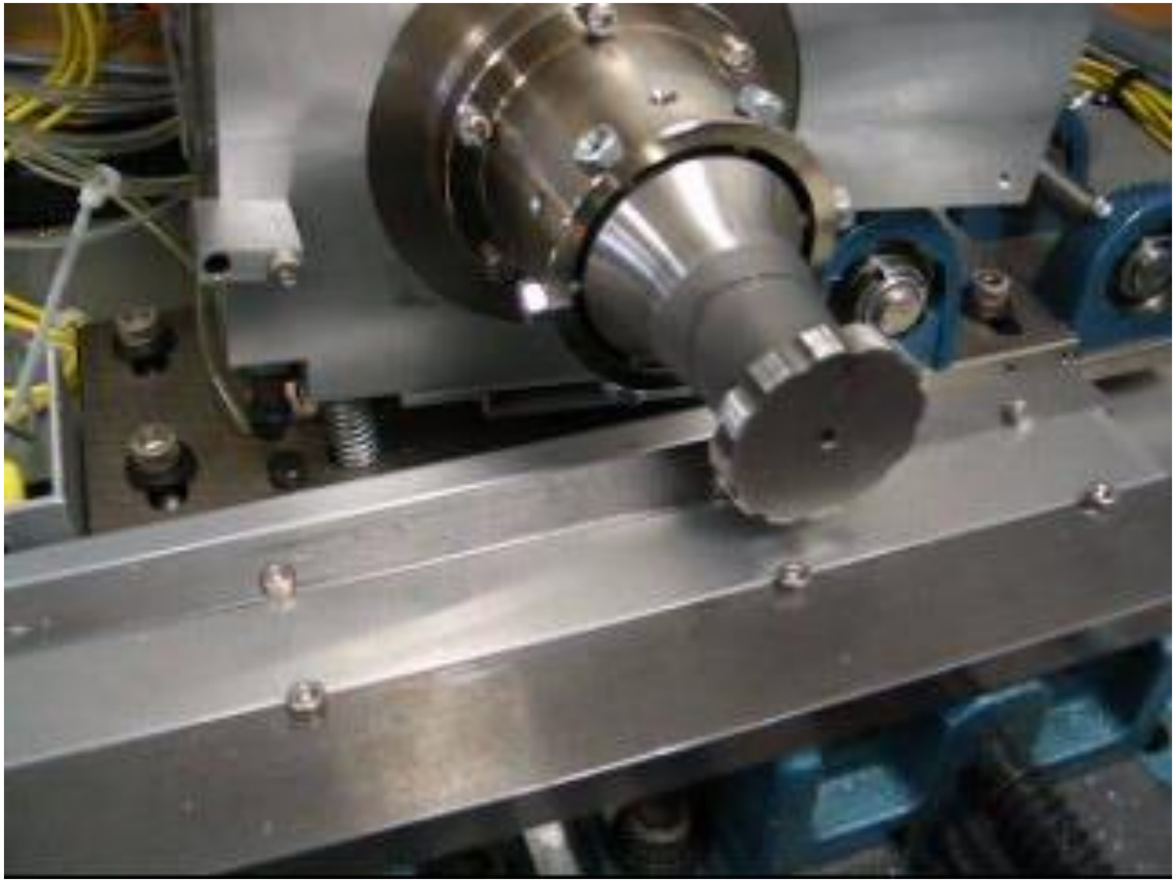
Heating during metal welding



Metal welding resonance

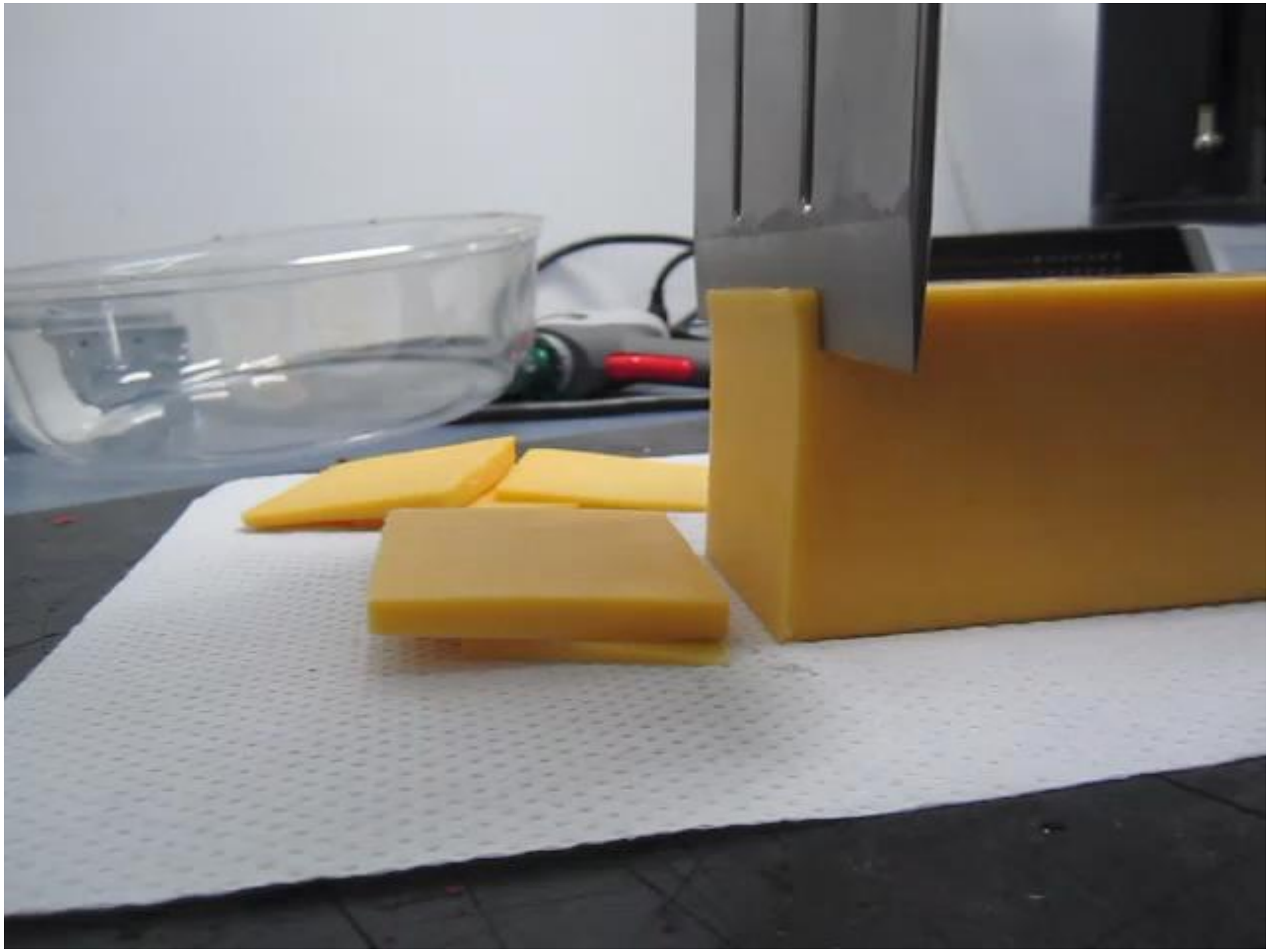


Metal welding continuous



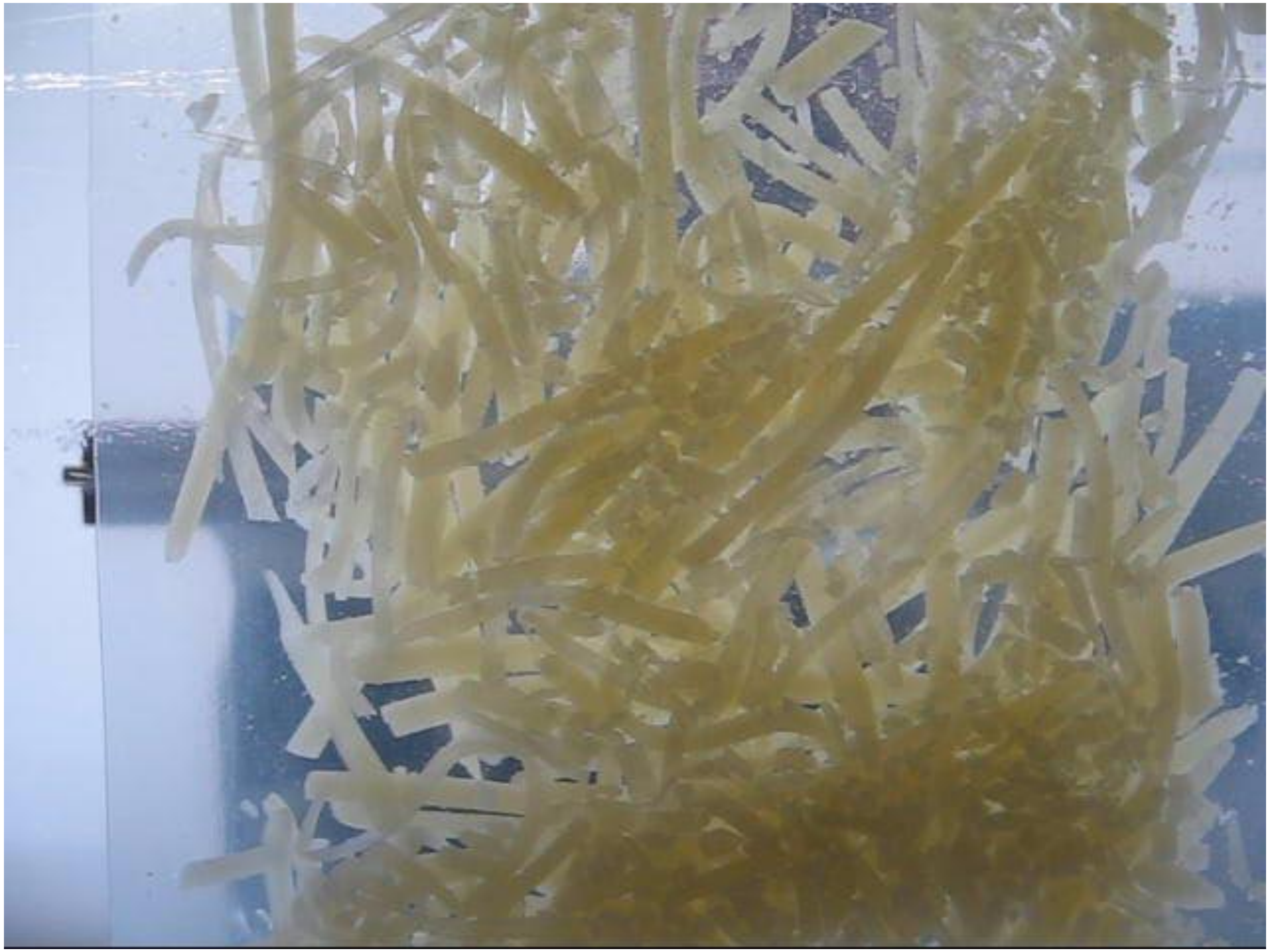
Cutting

Food cutting



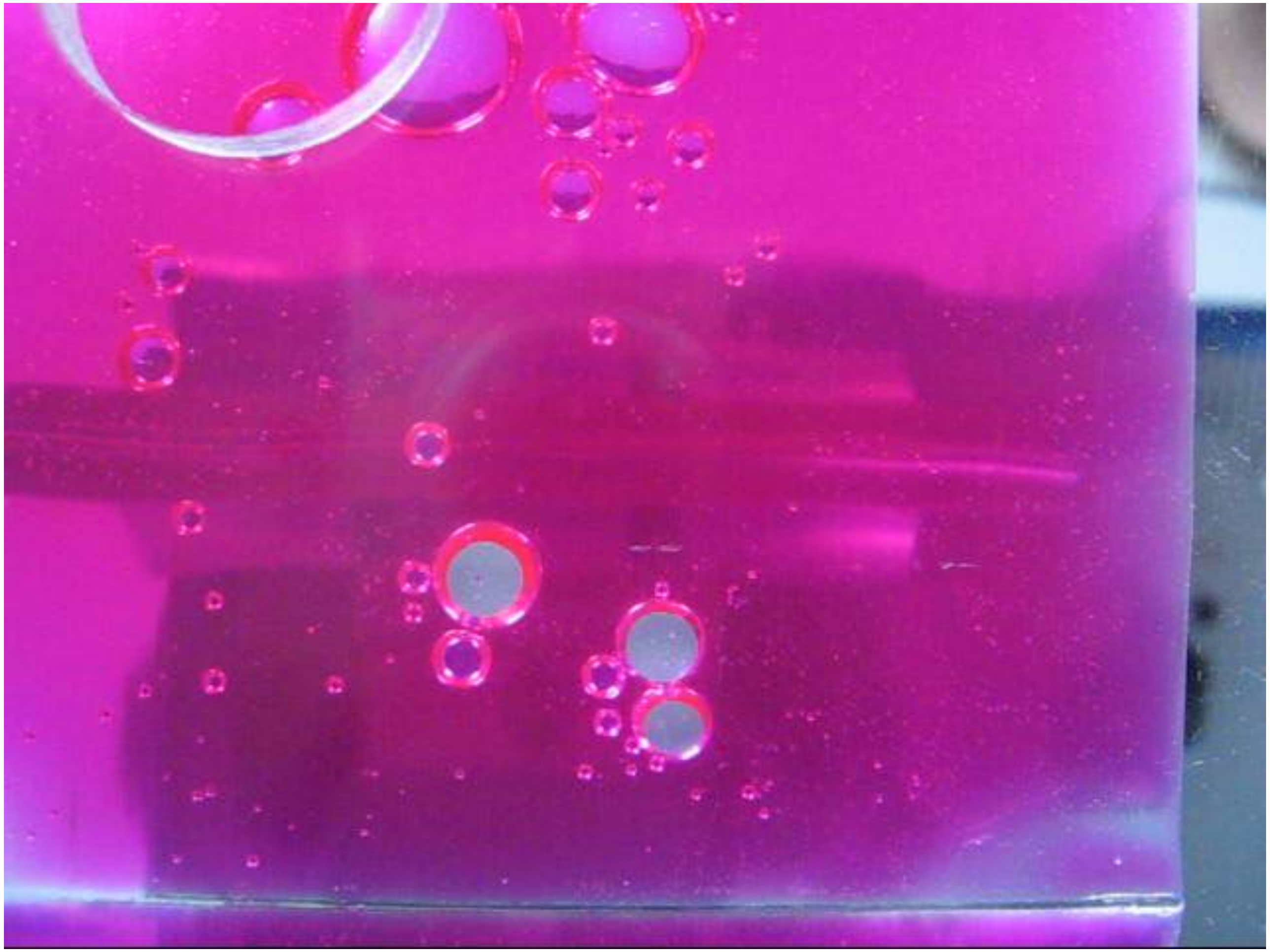
Dukane Ultrasonics

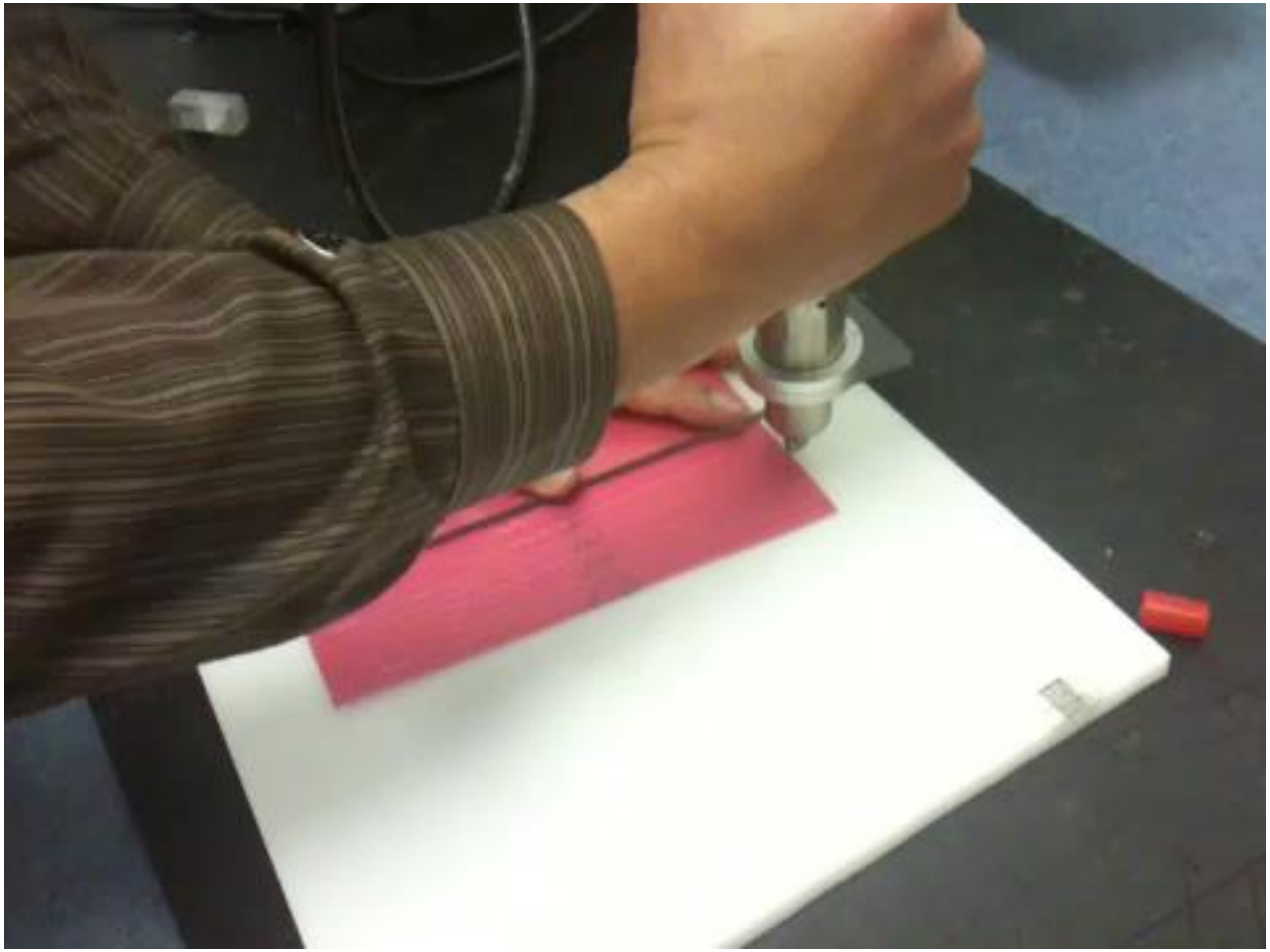
Food packaging-Cheese



Hermann Ul

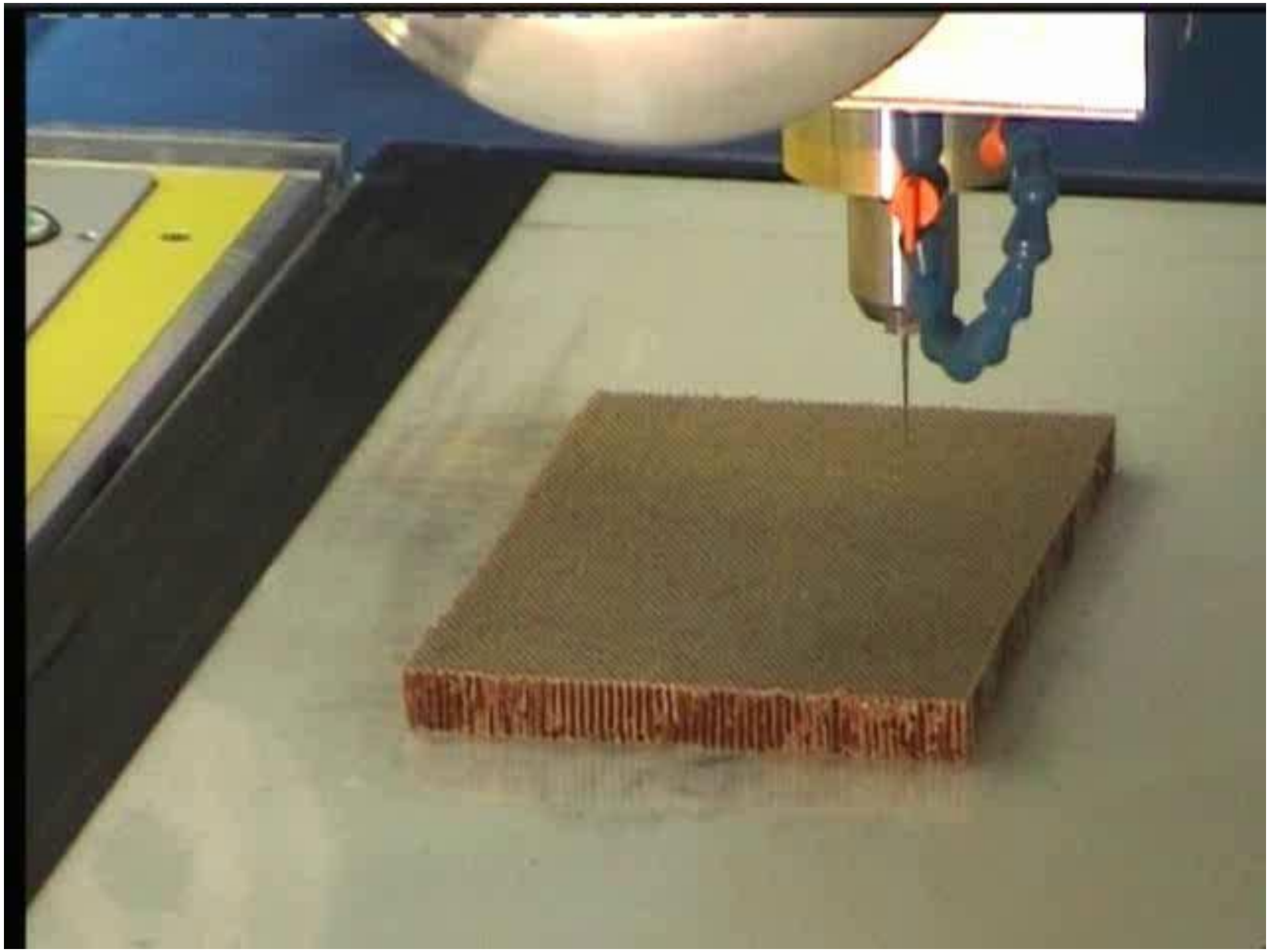
Food packaging-liquid





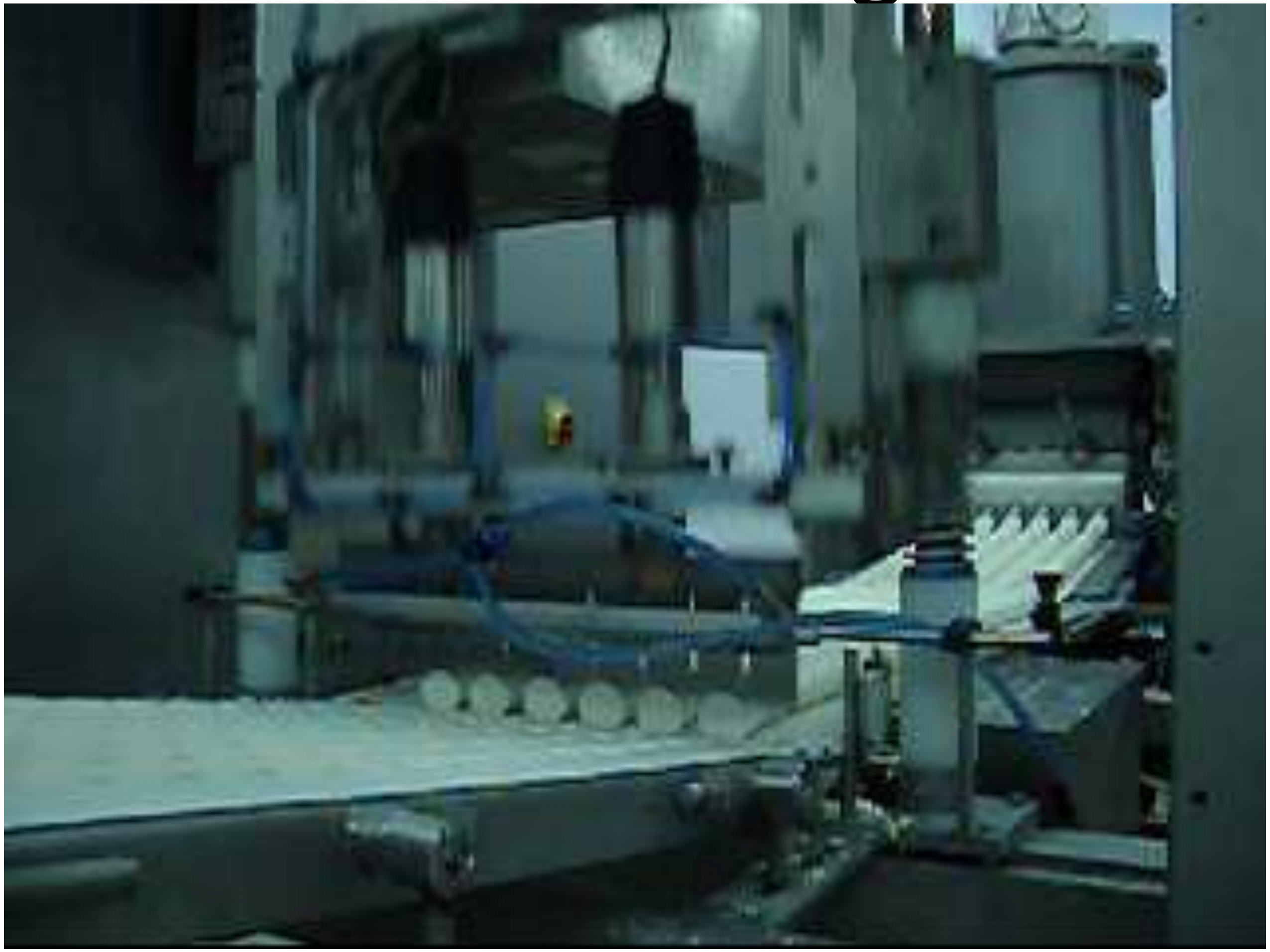
Dukane Ultrasonics

Cutting composites



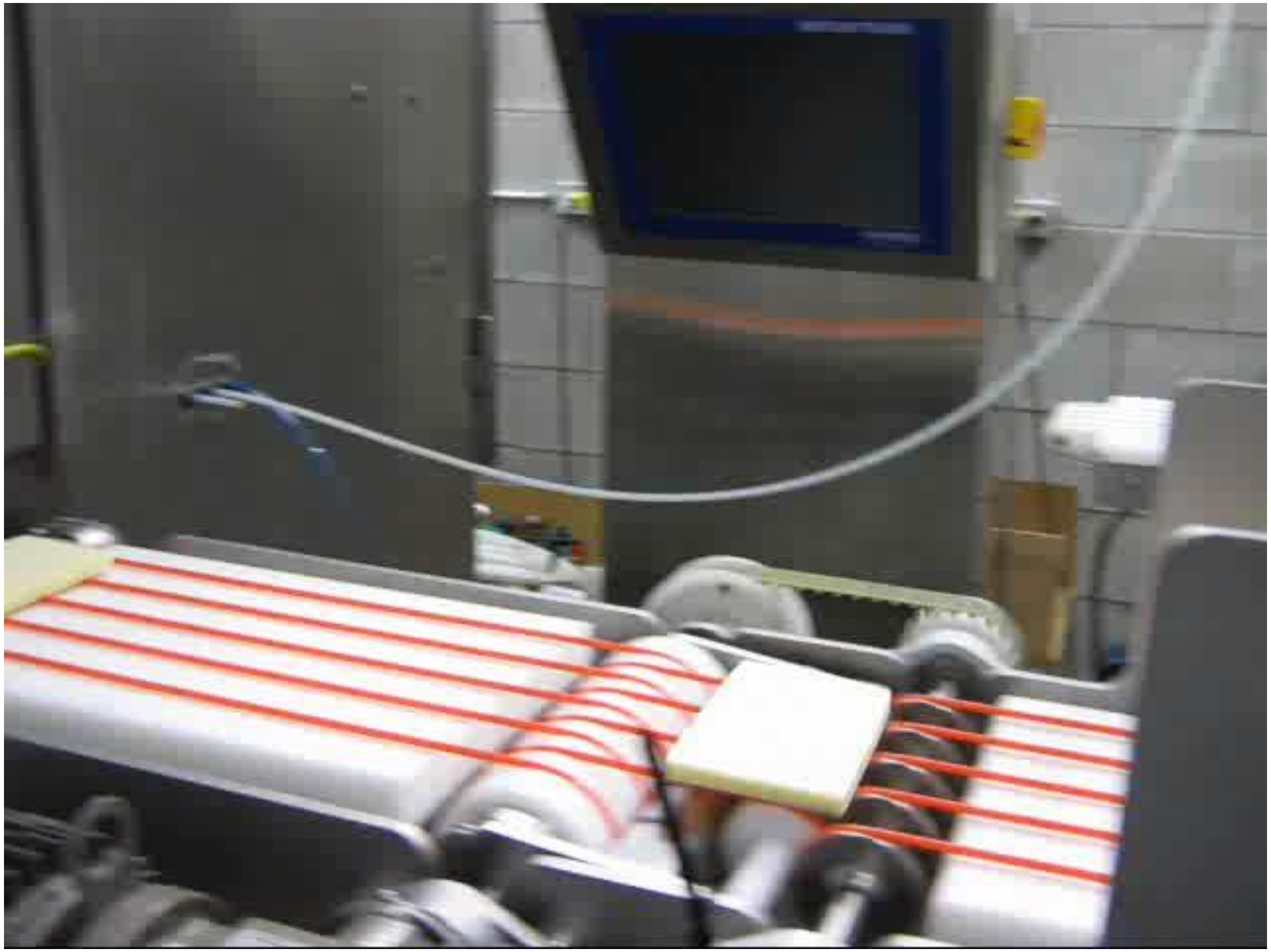
Dukane

Cookie Dough



Branson Ultrasonics

Cheese cutting



Branson Ultrasonics

Candy bar

Branson Ultrasonics

Defoaming

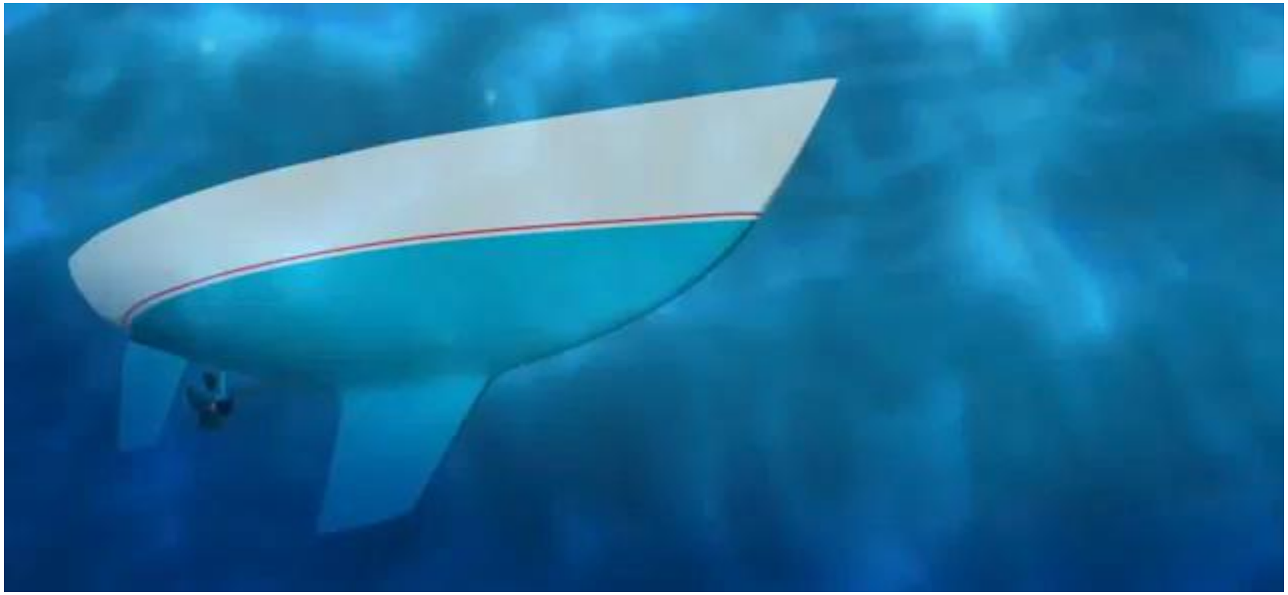
Advanced Power
Ultrasonic Technologies

PUSONICS

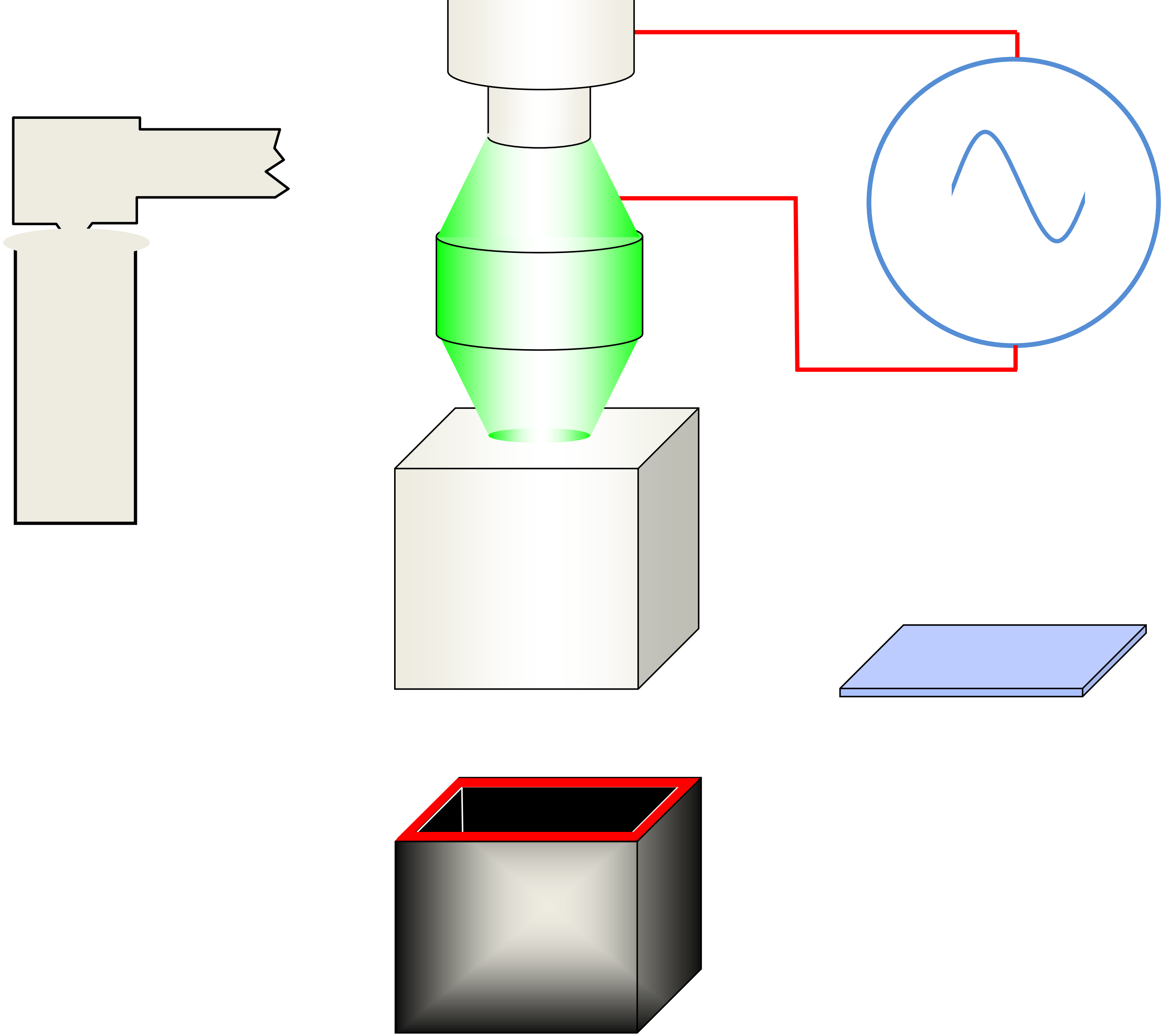
www.pusonics.com

Humidifier

De-foaling



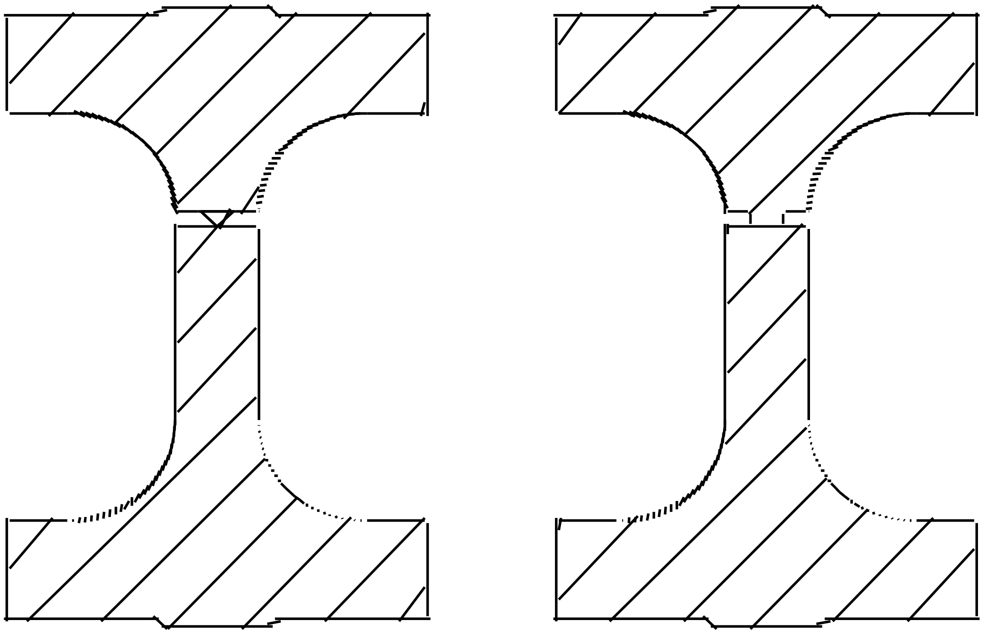
Plastic welding



Background

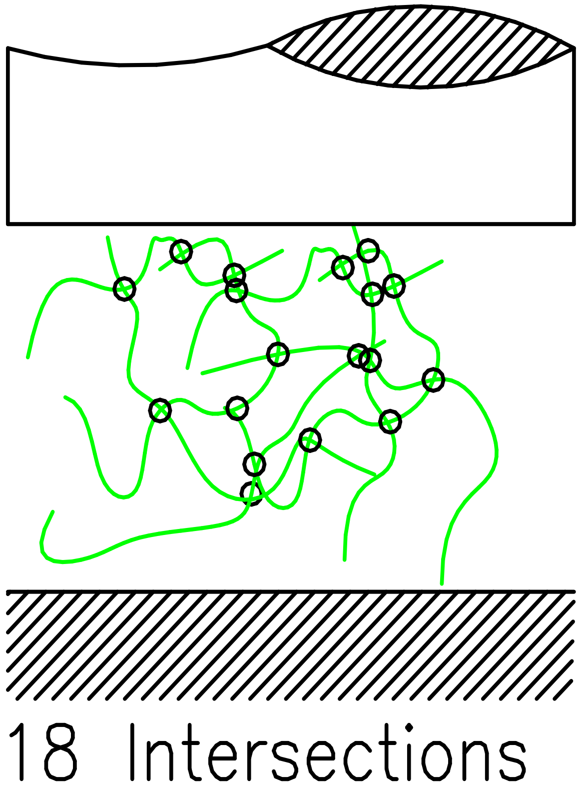
- Heating
- Joint design acts as stress concentrator
- Energy director, shear joints, etc.

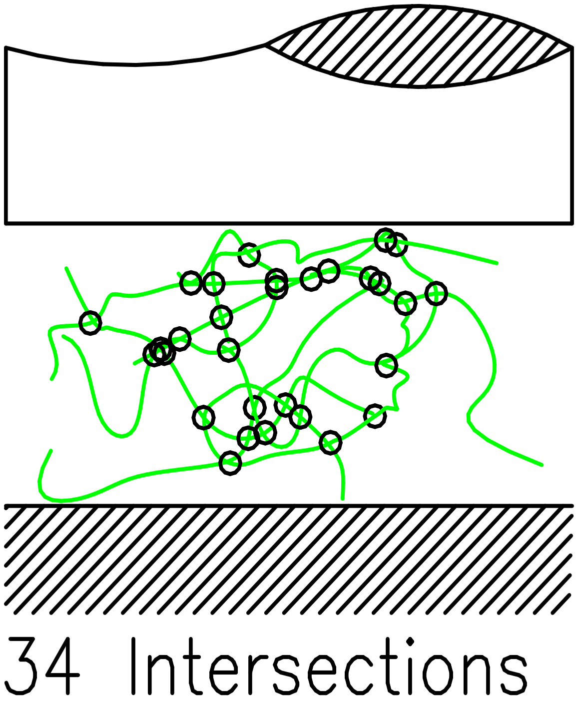
$$\dot{Q} = \frac{E''\omega\varepsilon_0^2}{2}$$



Background

- Molecular friction



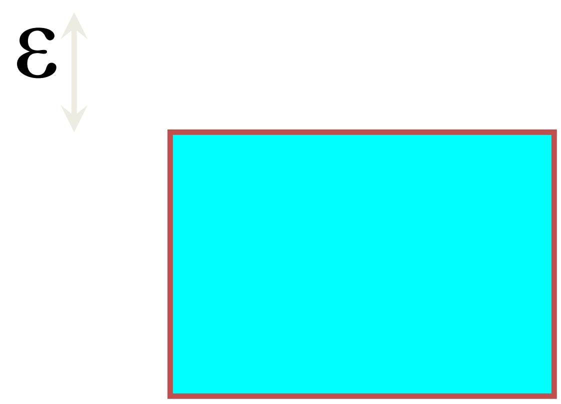


Background

- Heating
- Motion is a sinusoidal function
  - ε:strain amplitude
  - ω: Frequency

$$\varepsilon = \varepsilon_0 \cos(\omega t)$$

$$\sigma = E\varepsilon$$



Background

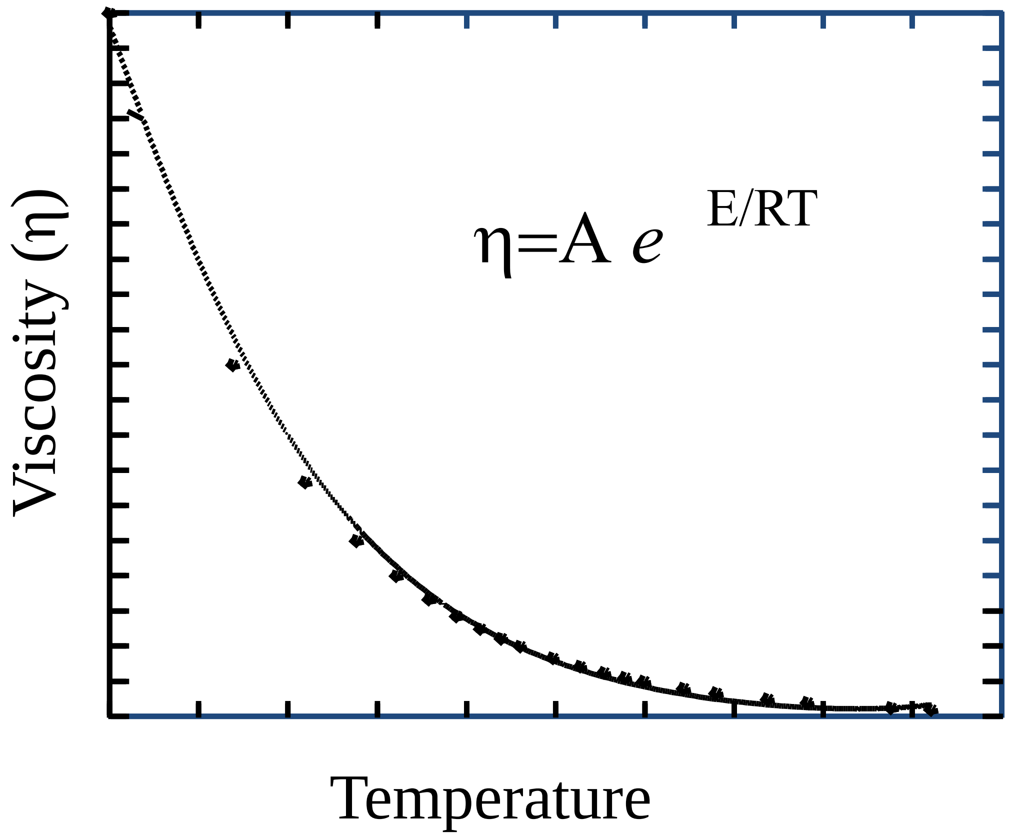
- Thus average heating:

$$Q = \frac{E''\omega\varepsilon_0^2}{2}$$

  - Temperature:
    - Frequency (ω) Constant
    - Amplitude (ε) Key parameter
    - E”-Loss modulus is difficult to define
  - Controlling the amplitude allows temperature control!
  - The wrong temperature, dinner is ruined!!

Background

Melt viscosity of plastics:



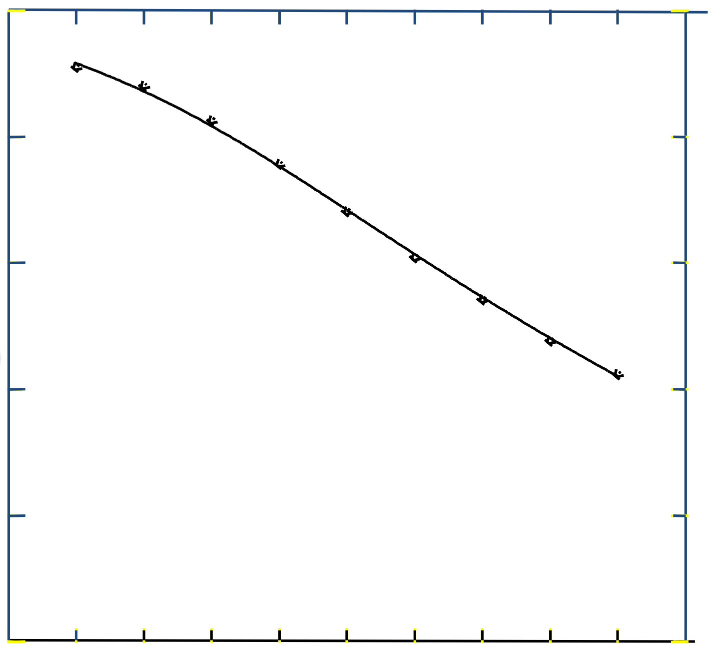
Background

Melt viscosity of plastics:

Melt viscosity of plastics:

$$\dot{Q} = \frac{E'' \omega \varepsilon_0^2}{2}$$

Viscosity (η)



Induced strain (Amplitude)

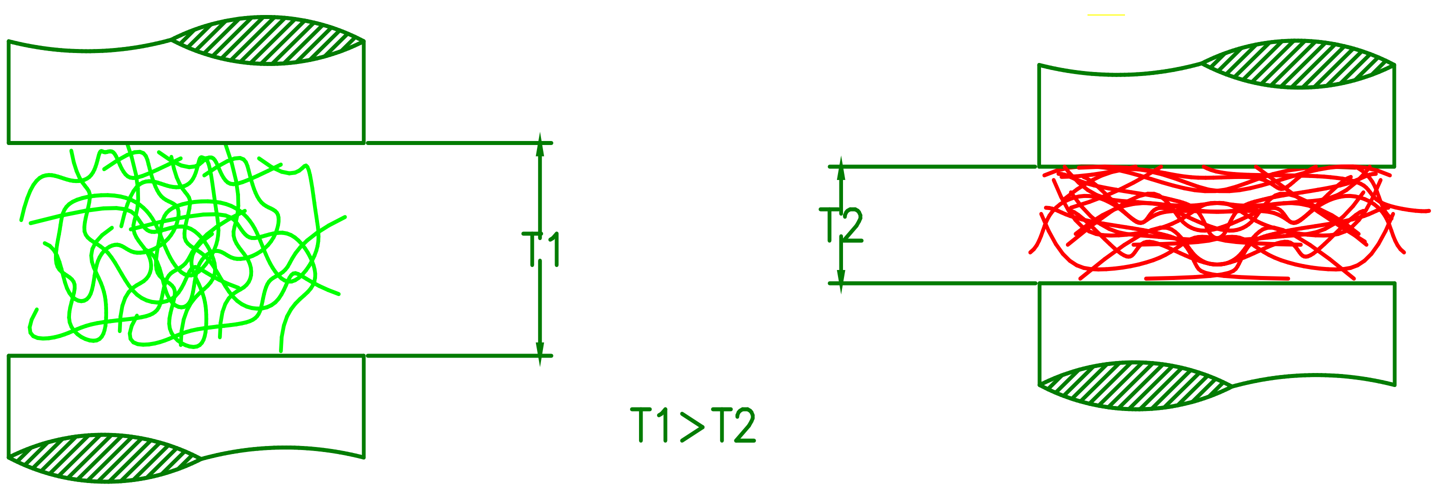
Amplitude $\approx \varepsilon$

$T \approx \varepsilon$

$\eta = A\, e^{E/RT}$

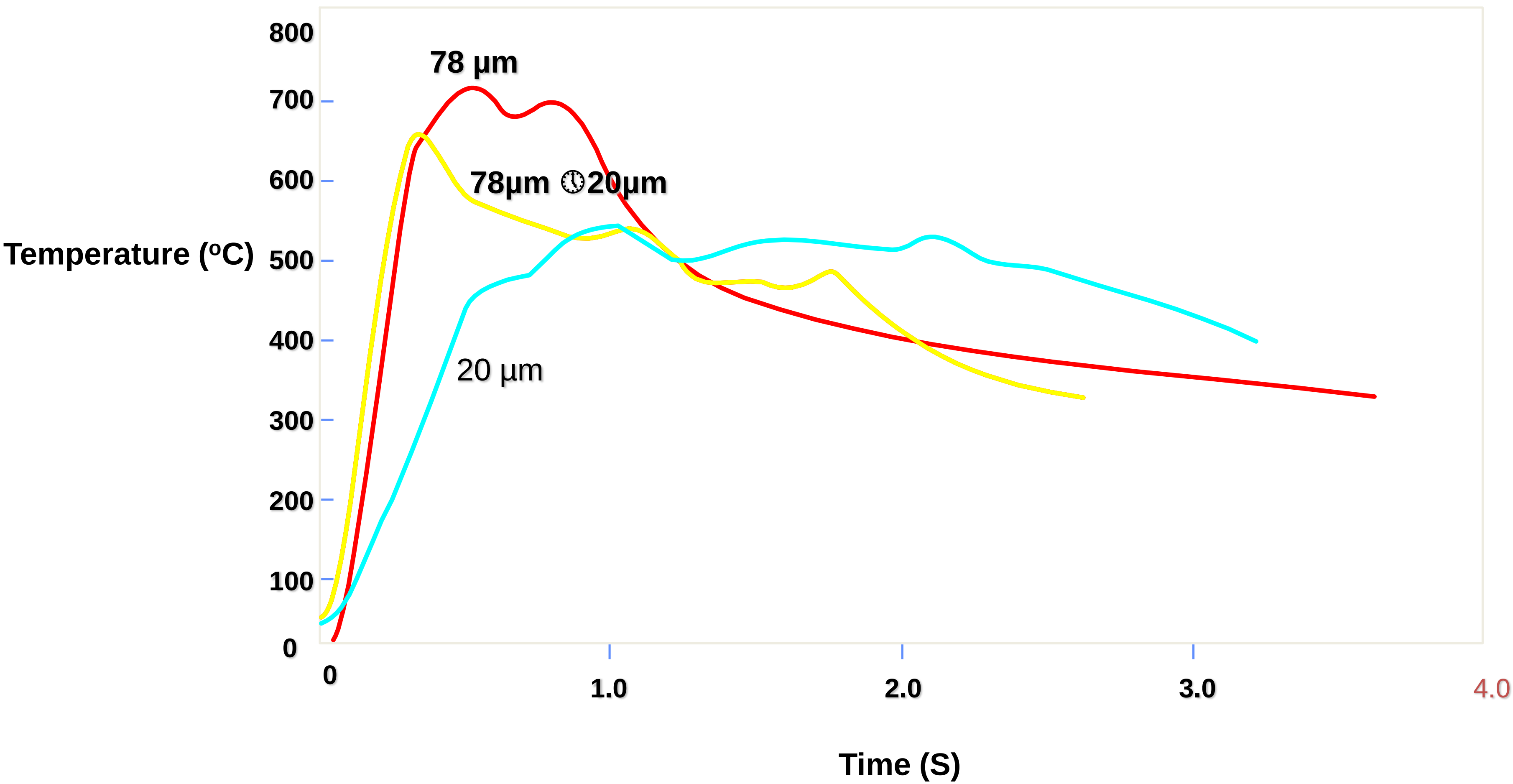
$\eta \approx 1/\text{Amplitude}$

Melt viscosity of plastics:

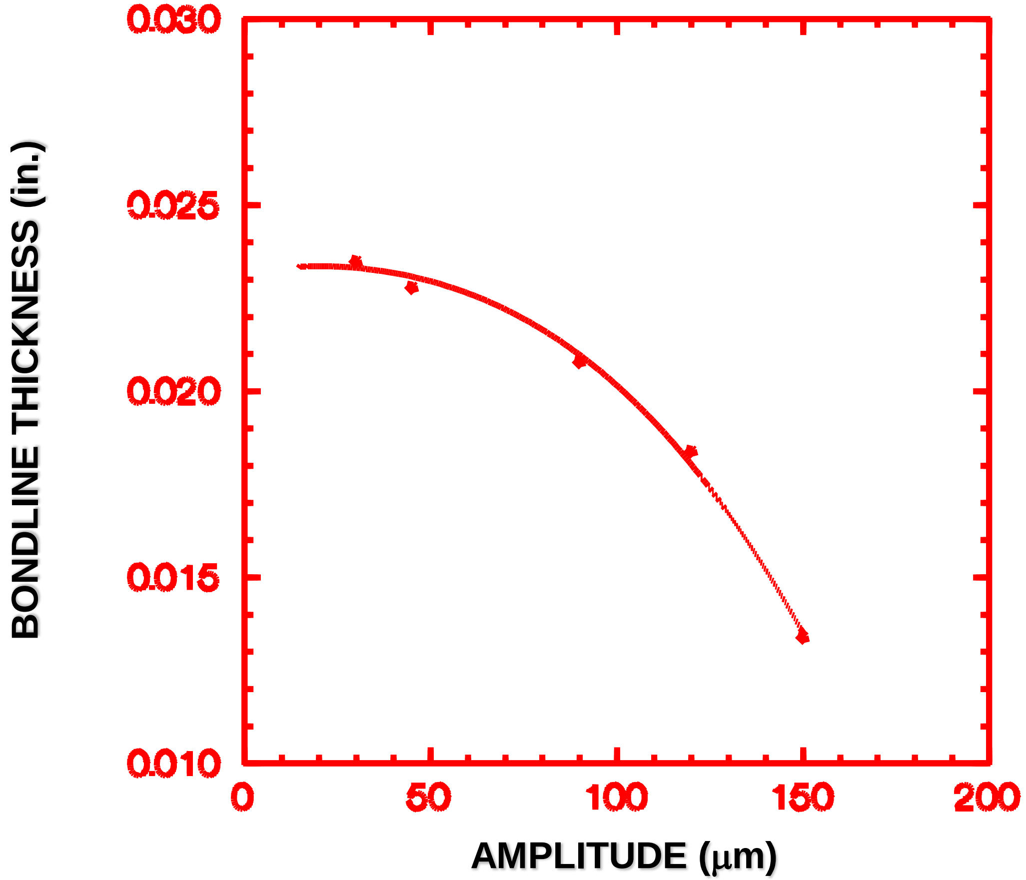


Bridging

No Bridging

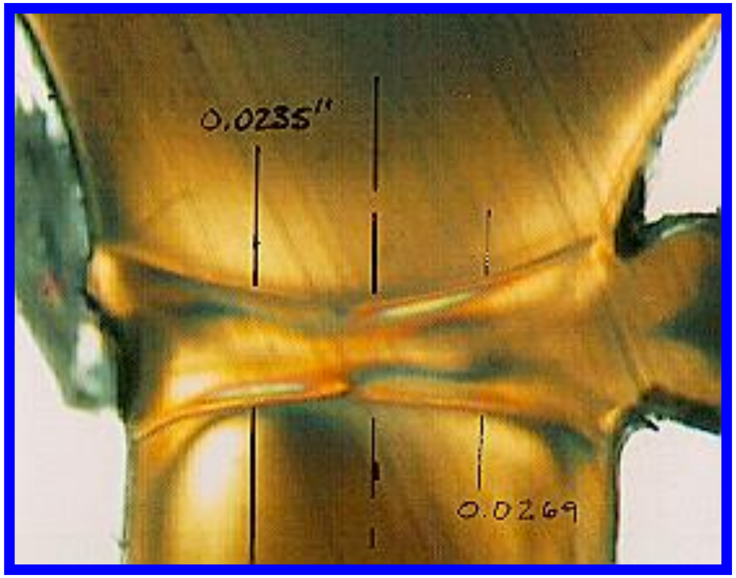

Temperature (ºC)
800
700
600
500
400
300
200
100
0
78 µm
78µm 20µm
20 µm
0
1.0
2.0
3.0
4.0
Time (S)

- With collapse constant:



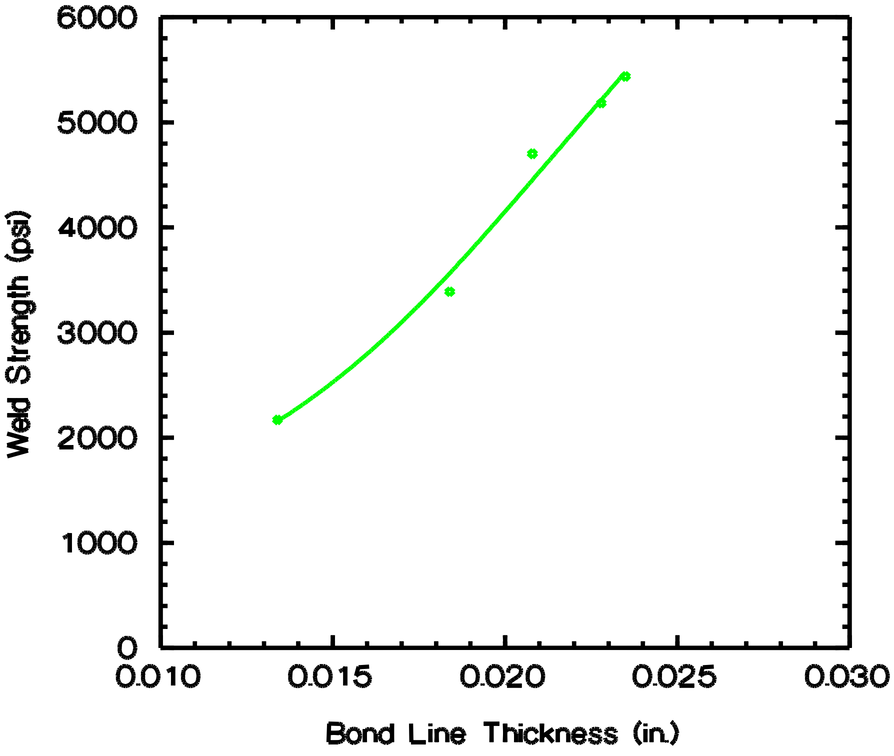
- Typical cross sections:

High Amplitude
Thin Bond Line



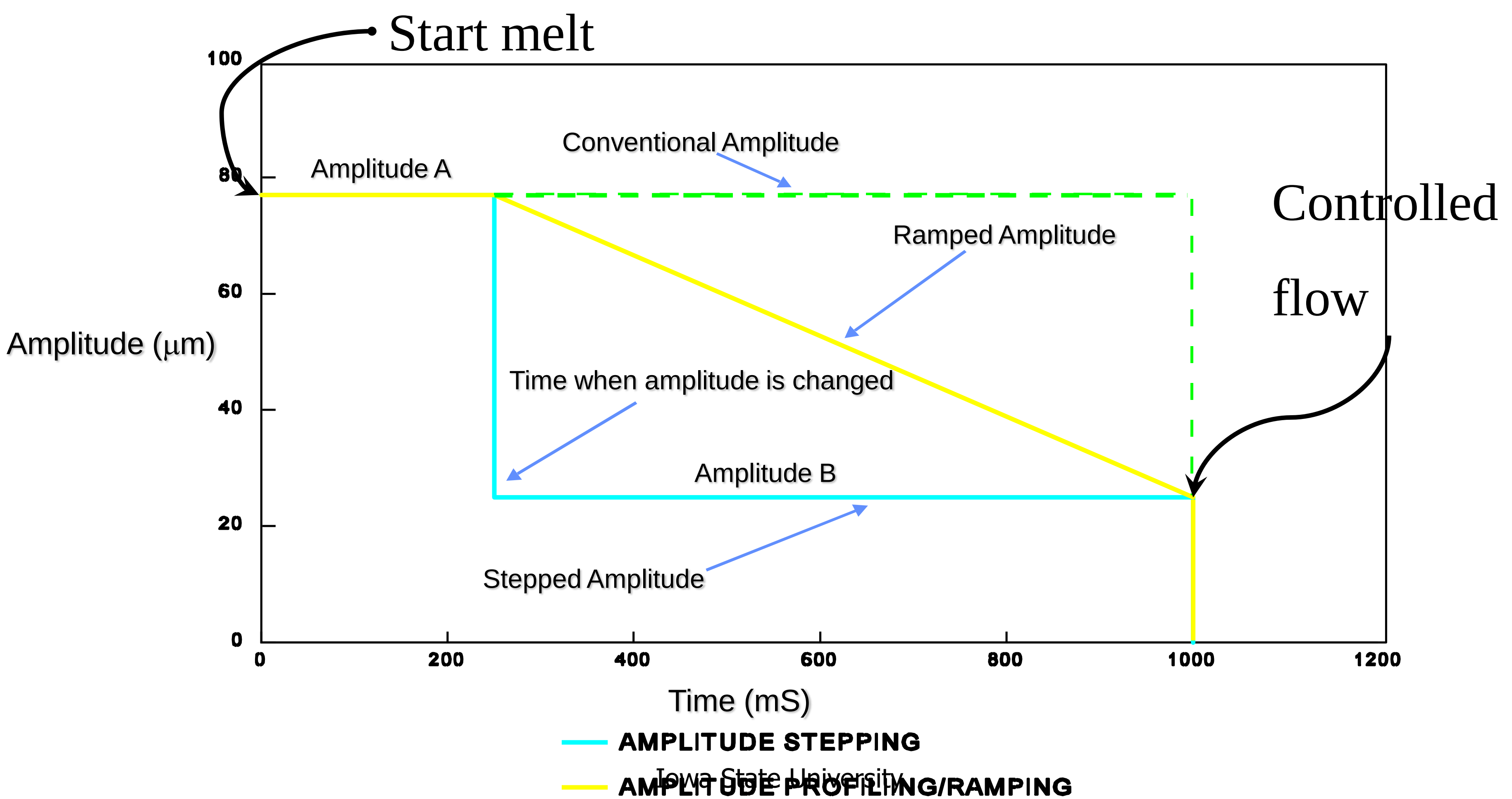
Low Amplitude
Thick Bond Line

- Amplitude and weld strength:



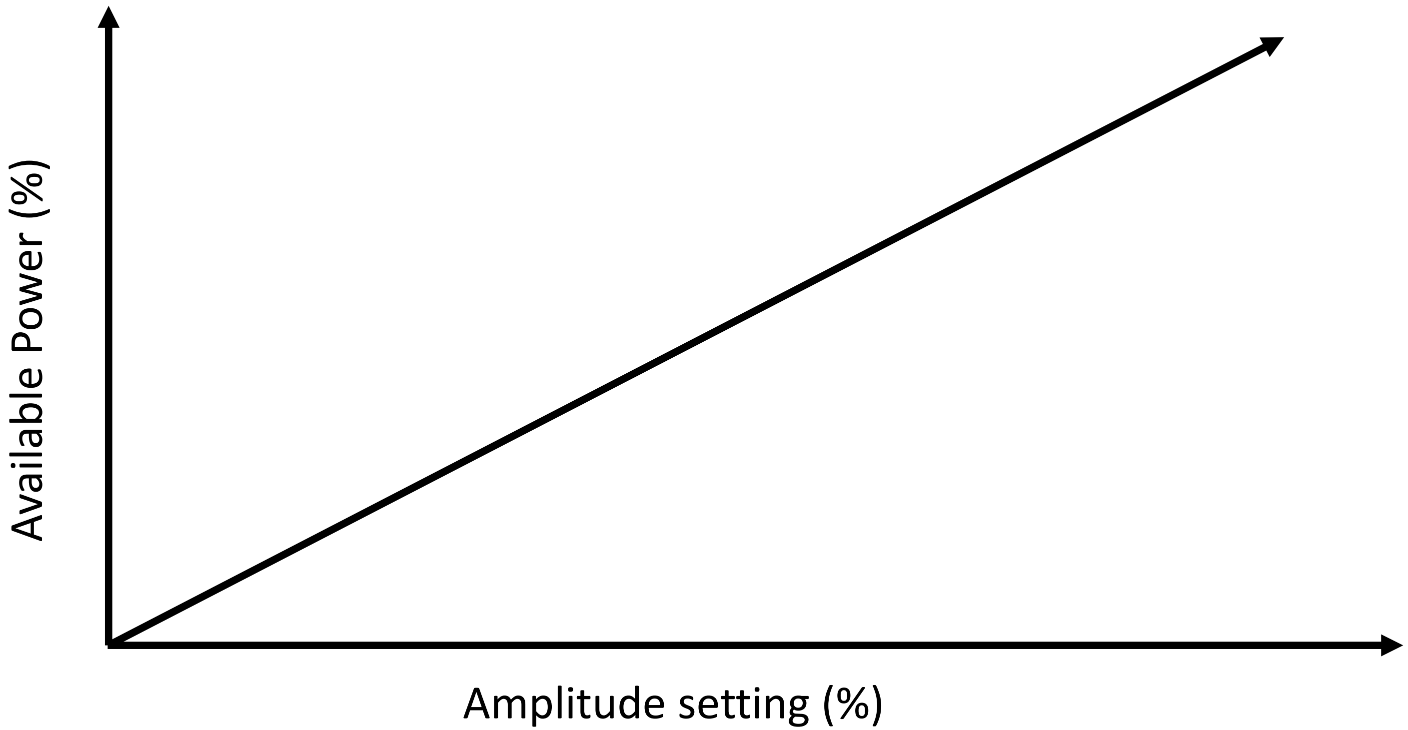
IOWA STATE UNIVERSITY

- Amplitude profiling



Amplitude profiling

- P= V x I
- Current is limited by wire size



Tooth paste tubes

Branson Ultrasonics

Blister pack

Branson Ultrasonics

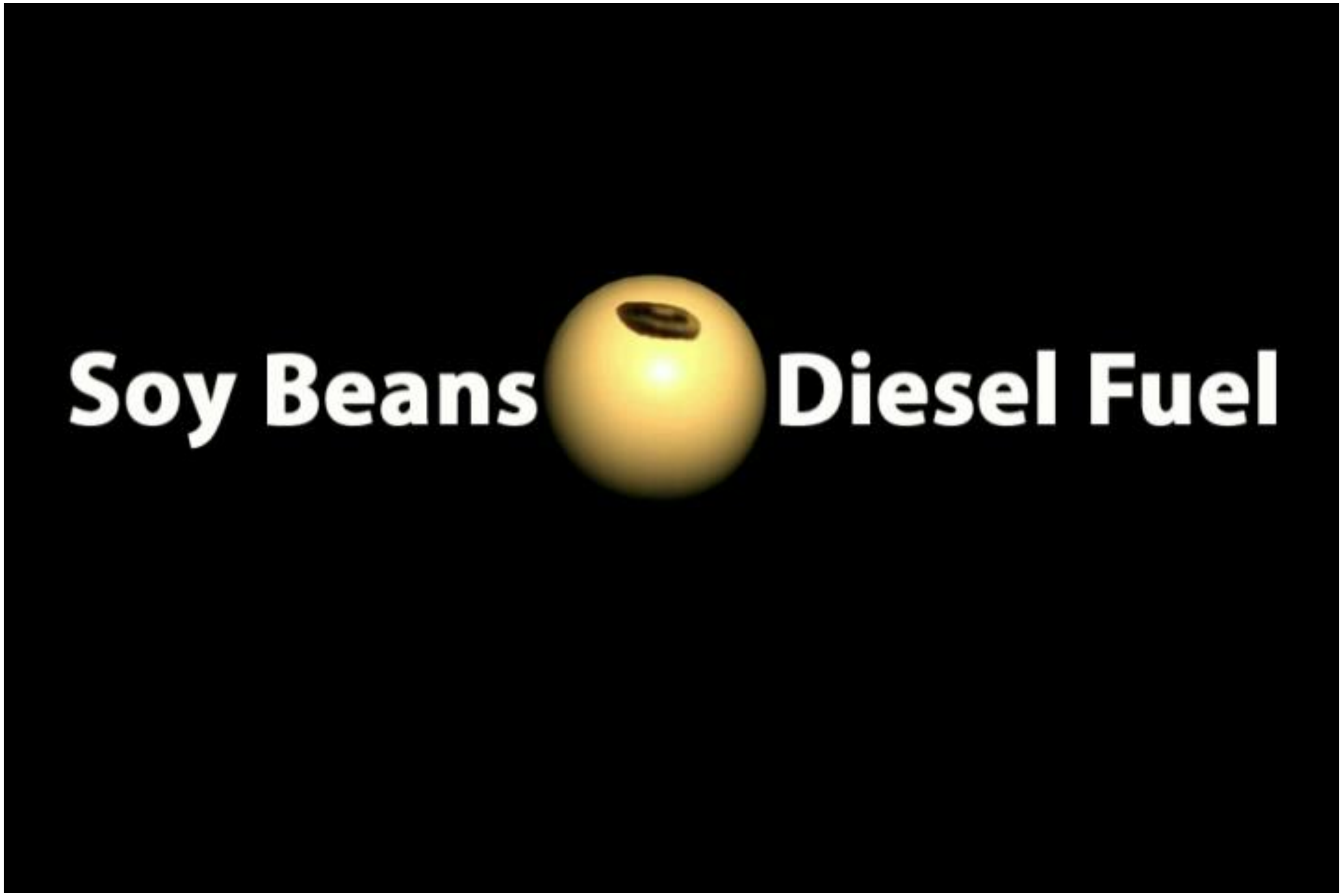
Other industrial application

- Rock cutting
- Additive manufacturing
- Particle removal
- etc

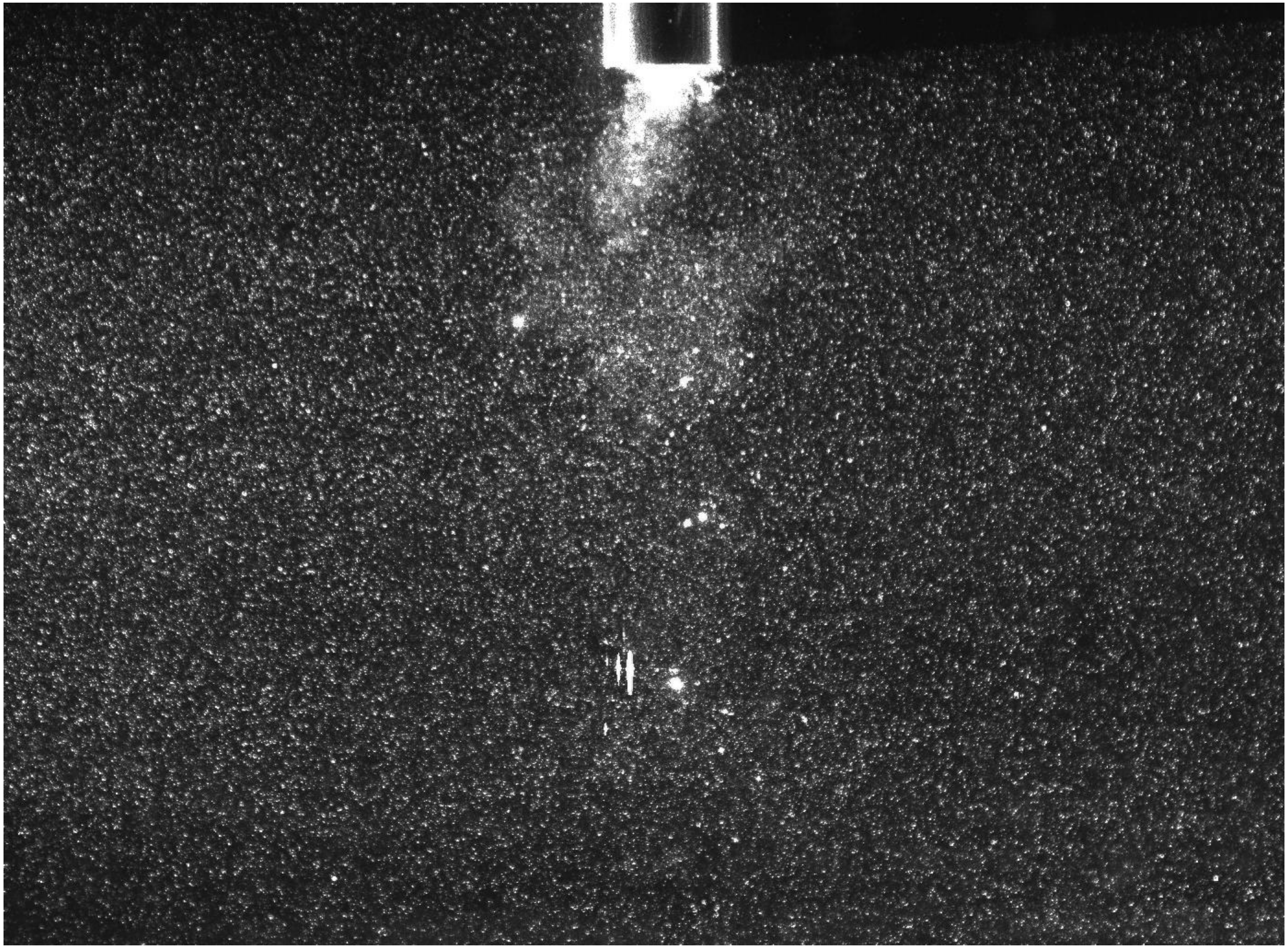
Chemical processing

- Biofuels
  - Enhance biodiesel (60 min to 15 s)
  - Enhance ethanol (No jet cooking)
  - Ionic liquids
  - etc

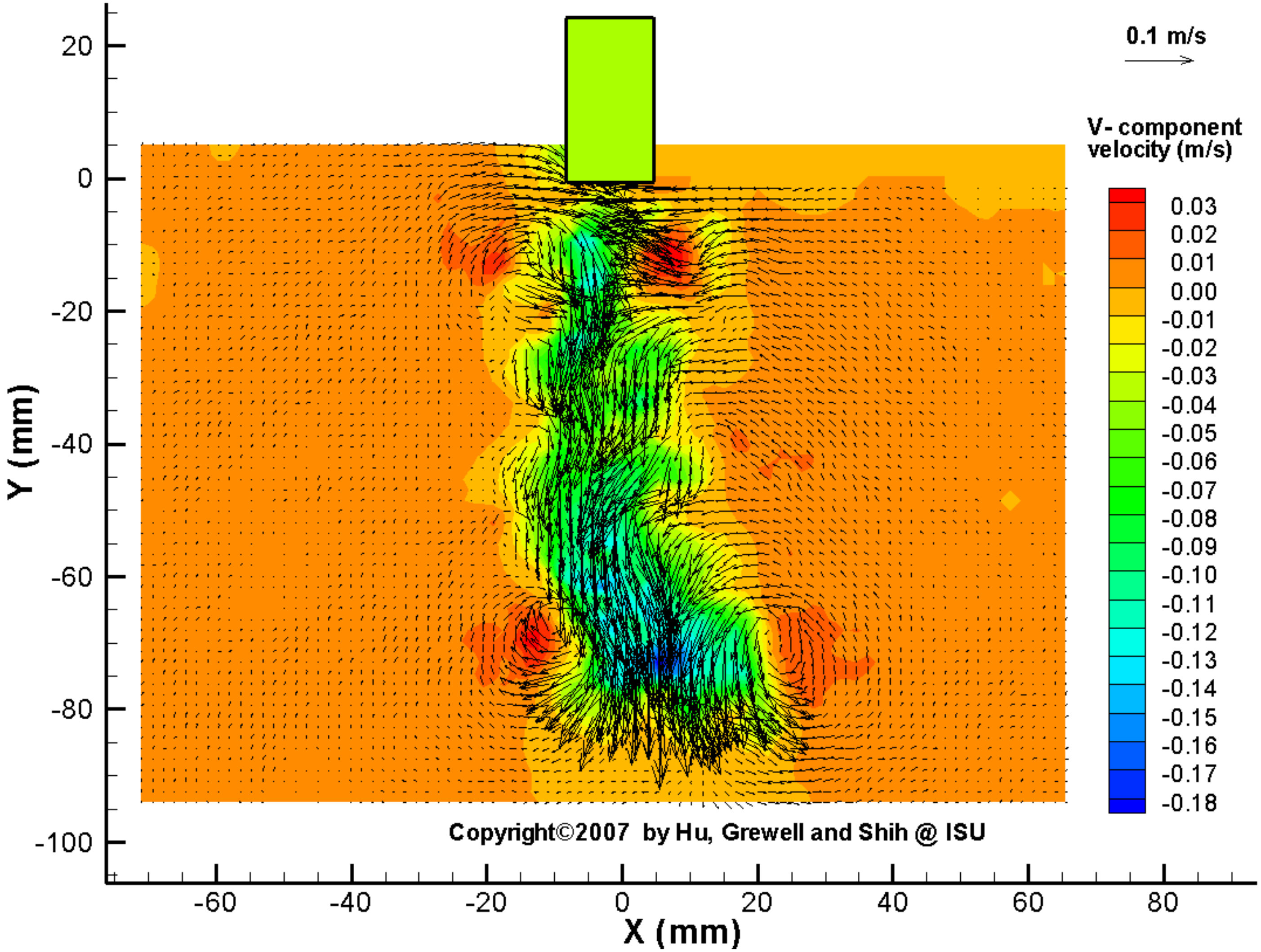
Biodiesel



Modeling of liquid processing



Modeling of liquid processing



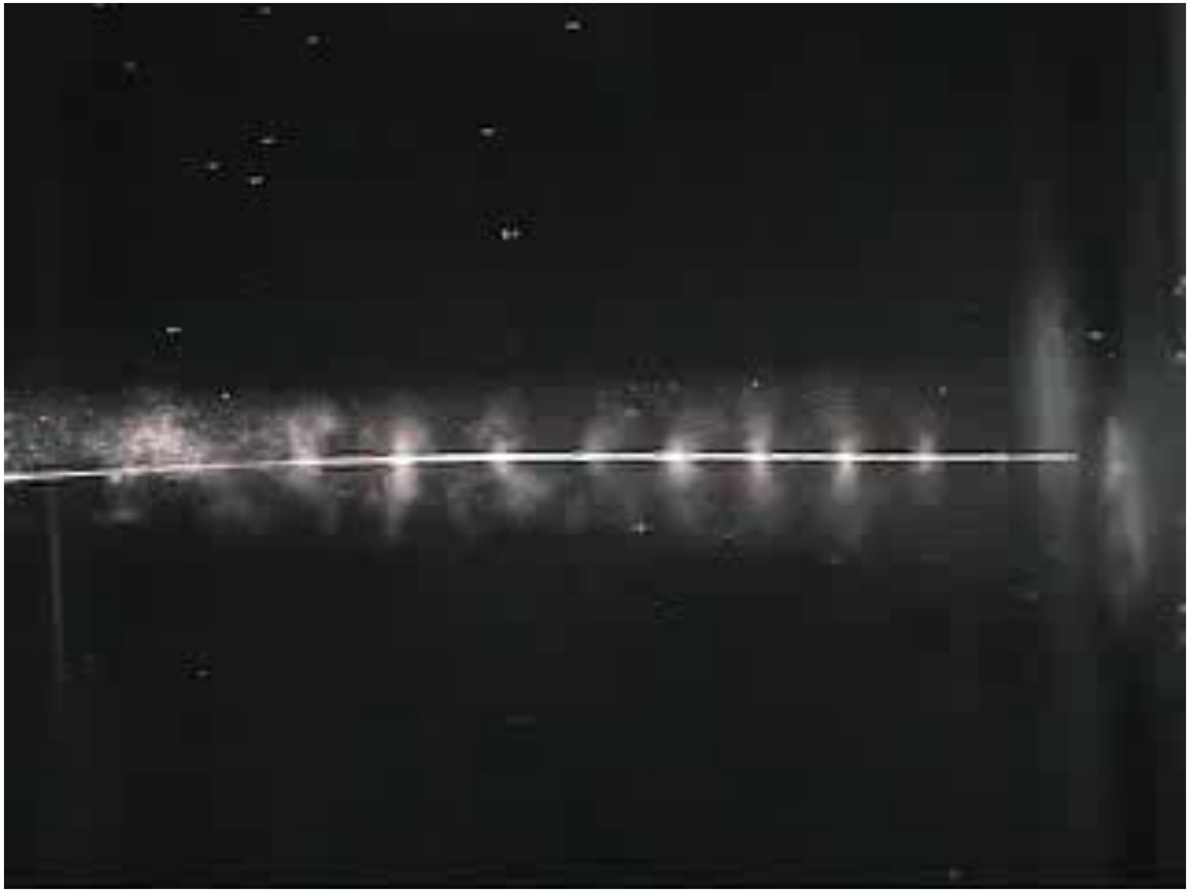
Water treatment

Sonix

Medical

- Drug delivery
- Cutting
- Adhesive removal
- Stone breaking
- etc

Plaque removal



Plaque removal

Thanks!!

- CIRAS
- UIA
- Questions
- Comments